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PLASMA OSCILLATIONS IN A LOW PRESSURE ARGON DISCHARGE

HOWARD T. WEBB
AND
ALAN S. GARNER

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PLASMA OSCILLATIONS
IN A LOW PRESSURE ARGON DISCHARGE

Howard T. Webb

and

Alan S. Garner

PLASMA OSCILLATIONS
IN A LOW PRESSURE ARGON DISCHARGE

by

Howard T. Webb

Lieutenant Commander, United States Navy

and

Alan S. Garner

Lieutenant, United States Navy

Submitted in partial fulfillment of

the requirements for the degree of

MASTER OF SCIENCE

IN

PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 5 8

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ABSTRACT

A review of selected previous work in the field of plasma oscillations, together with theoretical explanations of the oscillations, is given. The components of a gas discharge apparatus to investigate plasma oscillations are described, and vacuum system operating procedures are discussed. Detection of plasma oscillations in the tube, in the 700 to 1300 megacycle range, is demonstrated.

The writers wish to express their gratitude to Professors N.L. Oleson and C.E. Menneken of the U.S. Naval Postgraduate School for their continuing advice, encouragement and assistance in the execution of this project.

The technical aid and sustenance rendered by Mr. Milton K. Andrews, Mr. Kenneth C. Smith and Chief Opticalman A.N. Goodall, USN, of the Physics Department, is sincerely appreciated.

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1. Introduction

There is a growing interest in the nature of processes occurring in the electrical gas discharge, particularly in the field of low pressure discharges. Recent developments in fusion are fundamentally related to such discharges and there is reason to believe that electrical noise and sun spot activity may be due to similar phenomena. This thesis reports on the construction of a gaseous discharge tube designed for investigation of plasma oscillations in a low pressure argon discharge.

2. Plasma Characteristics

For over thirty years it has been known that radio frequency oscillations, called plasma oscillations by Langmuir, can be detected in gaseous discharges. The term plasma is applied to a region occupied by approximately equal numbers of positive and negative particles, so that a macroscopic charge neutrality exists. In the ordinary positive column of a glow discharge, the positive gas ions and negative electrons constitute the plasma. For sufficiently high pressures, any negative ions present would quickly recombine with the positive ions to form neutral molecules, since these two have comparable velocities. Such a region is highly conducting and therefore exhibits a relatively low average voltage gradient. The positive ions, electrons and neutral gas molecules may or may not be in thermal equilibrium. Since a plasma is ordinarily established by an electric field, the positive ion energies (temperatures) are usually greater than those of the gas molecules but much less than those of the electrons, which frequently have very high energies (temperatures)

In general, the ions and electrons may be assumed to have Maxwellian velocity distributions [1], although departures from this distributing do occur [2]. Under the influence of an electric field, the drift current density of electrons and positive ions is usually much smaller than the random current density so that the Maxwellian distribution is preserved, though ion and electron temperatures are increased. This increase in energy is greater for electrons than ions, since electrons have a greater mobility. Electrons lose little of their energy to the neutral particles but the ions will increase gas temperature by collision since their masses are comparable to those of gas molecules.

Although a sufficiently large volume of plasma is essentially neutral, microscopic volumes are not, due to variations in surrounding charge concentrations, resulting in varying and sometimes rather high fields at points throughout the plasma. The ionization of a plasma is maintained primarily by electron collisions and also by some photoionization [3].

Experiments on plasma oscillations in gaseous discharges are generally carried out in evacuated tubes, ordinarily diodes, maintained at varying pressures. The glow discharges of interest here utilize mercury, argon or similar gas at pressures in the low micron range, (up to 30 microns), at plate potentials of up to 1000 volts. Under these conditions the voltage variation across the tube consists of a steep rise, considering up as positive, from the cathode to the beginning of the negative glow, a slow rise in potential across the remaining length of the tube, and a small sharp rise to the anode. Thus the cathode fall, as it is termed, constitutes the major voltage rise

which electrons cross in passage to the anode. Since electron mobilities are greater than positive ion mobilities, the cathode is ordinarily surounded by a positive ion sheath. That portion of the discharge which is associated with the cathode, from cathode through the Faraday dark space, remains fixed in size as cathode anode distance is varied, so that frequently in oscillation experiments only those portions of the discharge through the negative glow exist between cathode and plate, the positive column not being present for sufficiently small cathode anode distances. In the negative glow, except at and close to the edge toward the cathode, the concentrations of positive ions and electrons are approximately equal so that the discharge here is considered a plasma [4].

Plasma oscillations are very high frequency oscillations which take place in the plasma of a gas discharge, due to local perturbation of electron-positive ion densities with later attendant modulation of passing fast electrons by means of a feedback or growing wave mechanism.

3. Previous Work

In 1924 Langmuir and Mott-Smith [2], in making investigations of the velocity distributions of electrons in a low pressure mercury discharge, discovered a group of "primary" electrons some of whose energies exceeded the potential across the experimental tube (Fig. 1). A discharge of this type has a large voltage rise across the cathode space charge sheath and the remainder of the tube is approximately at anode potential, so that electrons appearing beyond the cathode sheath would be expected to have energies approximating the tube potential. Others of the primary group had energies lower than

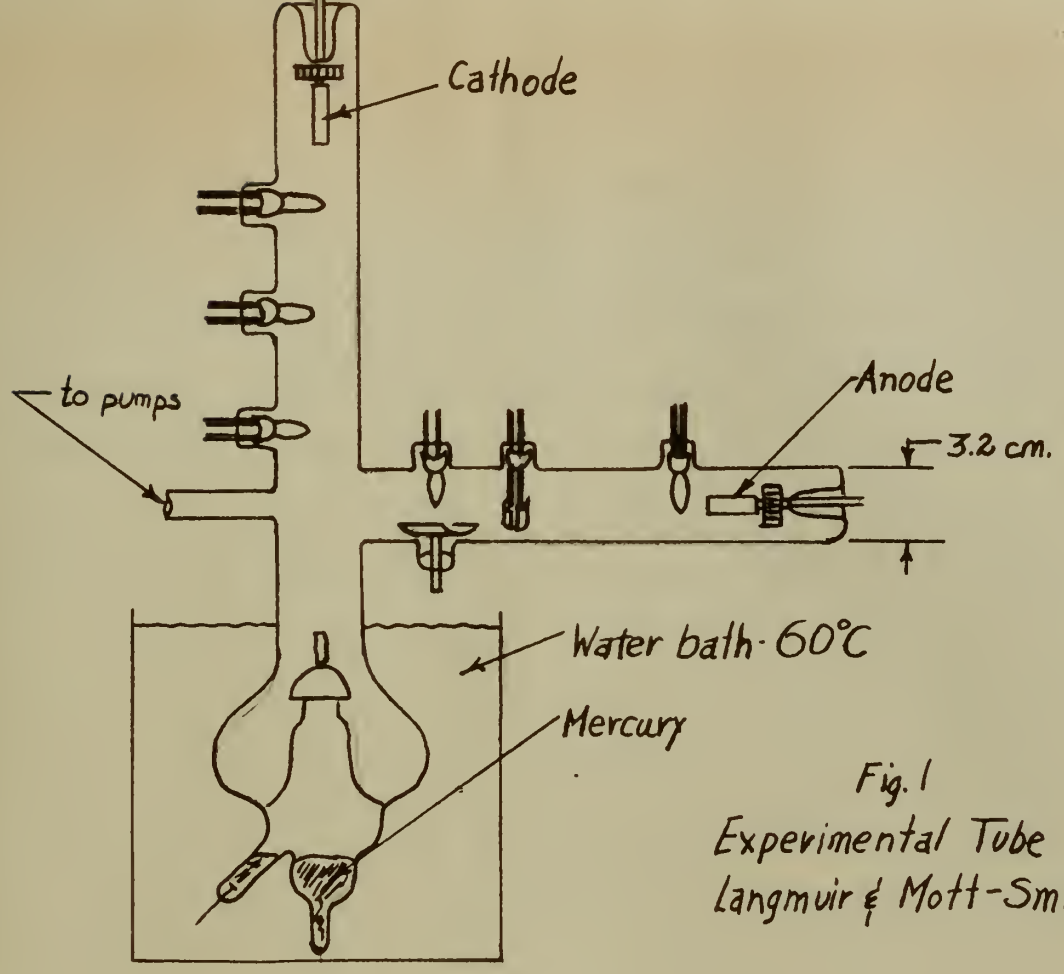


Fig. 1
Experimental Tube
Langmuir & Mott-Smith

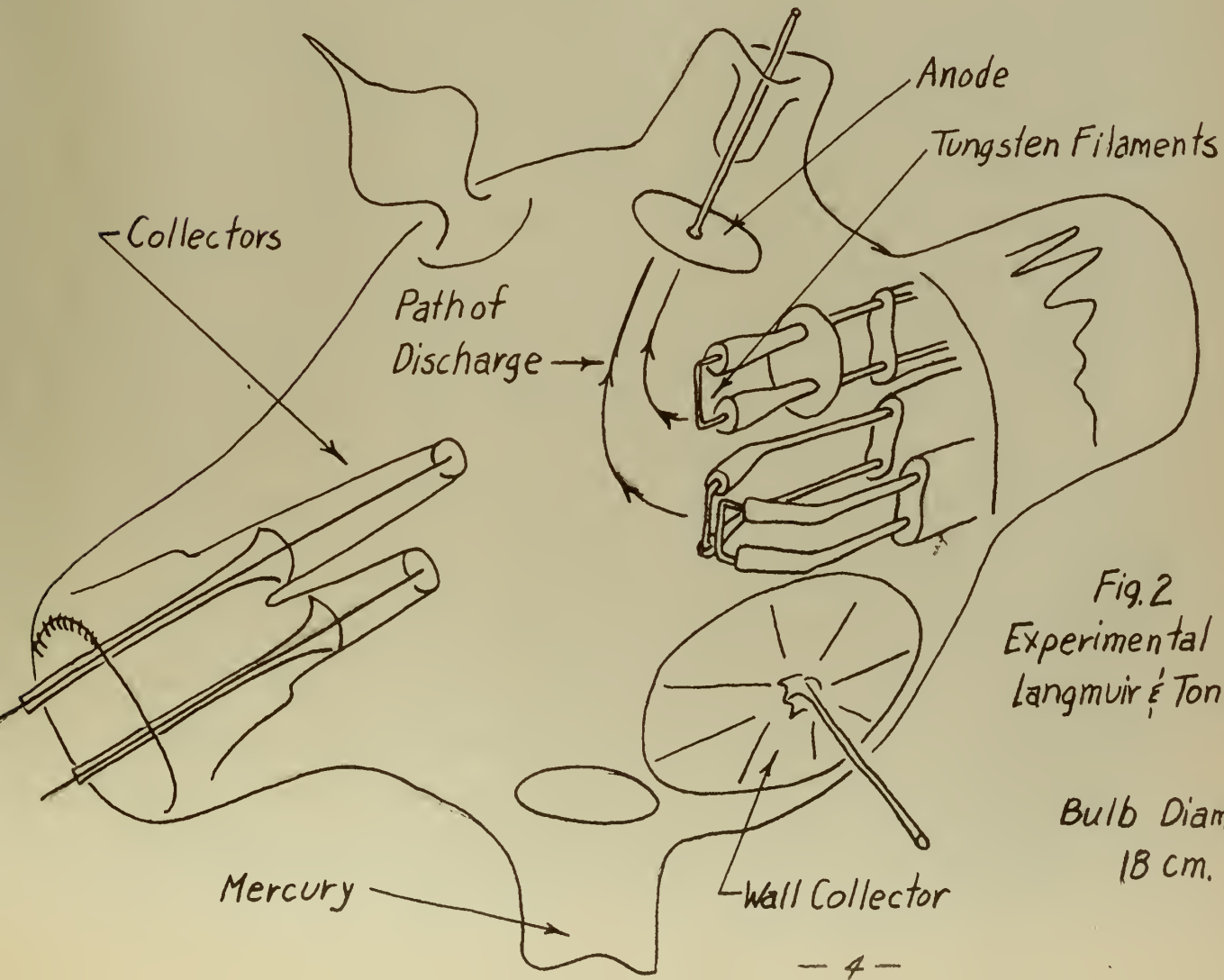


Fig. 2
Experimental Tube
Langmuir & Tonks

Bulb Diameter
18 cm.

expected, with the result that the energies were said to have been "scattered", though the mean energy of primaries was little changed. In 1925 Langmuir [1] described further experiments in similar discharges, and proposed several theories, later discarded, for the method of energy acquisition of the excess energy primaries. Dittmer [5] studied the variation in scattering with distance from the cathode, anode potential and current, and gas pressure and ascribed the existence of high scattered electrons to a fluctuating potential in the tube plasma due to oscillations of the plasma electrons which he was unable to demonstrate experimentally. Penning [6] discovered oscillations of frequencies from 300 to 600 megacycles and observed that electron scattering was accompanied by oscillations. In 1929 Langmuir and Tonks [7] confirmed the presence of oscillations in the 1-1000 megacycle range, finding oscillations generally throughout the range but obtaining resonance peaks under certain conditions (Fig. 2). They advanced a theory of electrons oscillating in a jelly-like positive ion plasma, which will be considered later, to explain the oscillations, and their results agreed closely with experimentally determined frequencies. Druyvesteyn and Warmoltz [8] found that the changes in electron velocity and concentration of the fast electrons in a low voltage arc from a hot oxide cathode occurred in very narrow regions, and postulated the existence of micro fields in the plasma to explain the effects. In 1939 Merrill and Webb [9] studied the dependence of electron scattering upon plasma oscillations in a mercury arc discharge. Their experiments were conducted with an oxide coated cathode at tube pressures of three to seven microns and plate currents of 20 to 100 milliamperes (Fig. 3). They determined electron temperature and electron concentration using the method of Langmuir and

Mott-Smith [2], the electron velocity distribution using an analysis of tube voltage-current characteristics, and the position and intensity of electron scattering and plasma oscilations by measurement with a 50 micron diameter tungsten probe six millimeters long. Plate to cathode distance was 1.5 centimeters. Data for a typical run were as follows:

Gas pressure	3 microns
Plate current	20 milliamperes
Arc drop	-11.7 volts w.r.t. anode
Space potential	+8.1 volts w.r.t. anode
Cathode potential	-19.5 volts w.r.t. space potential

The first scattering occurred at 4.3 millimeters from cathode, in an area 0.2 millimeters wide, showing electron energies to 26 electron volts. The second scattering occurred at 6.1 millimeters from the cathode, of the same width, with energies to 33 electron volts. There was little further scattering from the second area to the anode. Each scattering area was closely followed by a region where oscillations of 1180 megacycles were noted, creating a current of five millivolts across a crystal detector. The first oscillation was detected at 5.3 millimeters from the cathode and the second and much more intense at 6.8 millimeters from the cathode. Further runs, varying the plate current and gas pressure, showed that an increase in either one caused the oscillations to diminish in intensity and the oscillation and scattering areas to move simultaneously toward the cathode. At 50 milliamperes and seven microns pressure, for example, no oscillations were detectable, whereas at 20 milliamperes and the same pressure, intense oscillations were detected (Fig. 4). The oscillation

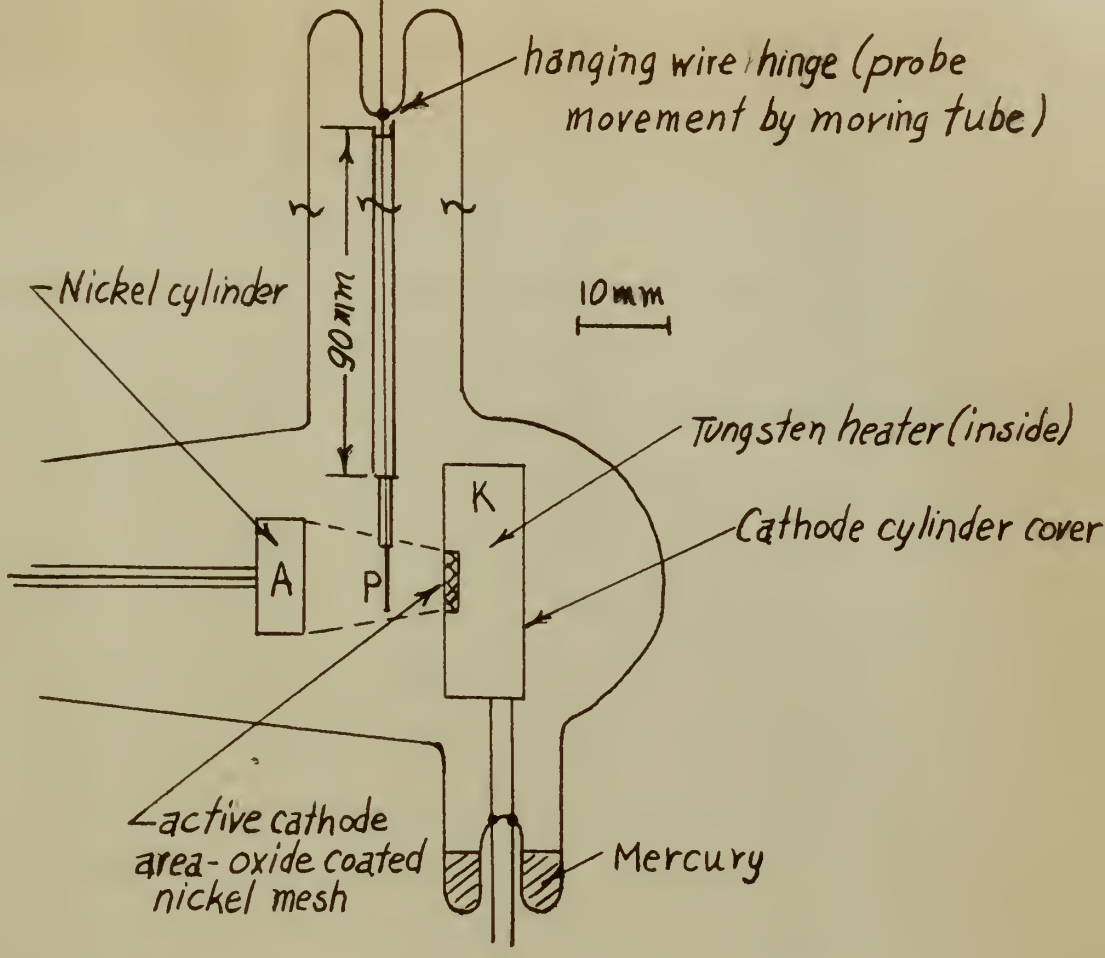
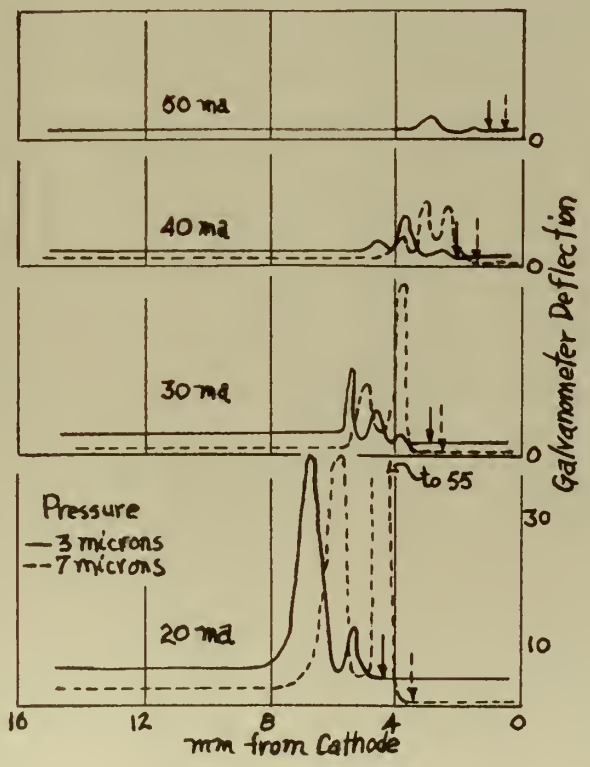


Fig. 3 Experimental Tube, Merrill & Webb



Note decrease in signal size and movement toward cathode with increase in tube current.

Fig. 4 Detector Galvanometer Deflection vs. Probe Position

and scattering regions were found only in areas crossed by primary (high velocity) electrons. Merrill and Webb thus confirmed the data of Druyvesteyn and Warmoltz, that the changes in electron velocity and concentration of the fast electrons occurred in narrow regions. The frequencies of their oscillations corresponded within ten percent to those predicted on the basis of electron concentration by the Tonks and Langmuir formula [7]. They concluded that oscillating plasma (ultimate) electrons received energy from the primary electrons in passage through the plasma and in turn scattered the primaries. They explained the difference in location between scattering and oscillation detection regions by saying that the primaries required transit time in order to bunch, after having been through the oscillating region, and they showed that the oscillations detected were due to collected primaries, not ultimates.

Armstrong, Emeleus, and Neill [10] continued the investigations of Merrill and Webb in tubes with coaxial wire filaments and surrounding anodes, and with round plate anodes and various other combinations of symmetrical and nonsymmetrical geometry, using tungsten and oxide coated cathodes. Tube pressures were on the order of microns in both argon and mercury vapor, and plate currents varied from 30-300 milliamperes. Typically, using a coaxial tube with tungsten filament and argon gas at 18 microns, they discovered three areas of oscillations:

Area	Plate Current [milliamperes]	Wavelength [centimeters]
1	140-150	14.0-14.8
2	209-230	9.4-8.9
3	304-307	5.6-5.2

The areas were associated with positions on the tube current-voltage characteristic, area 1 above being below current saturation, area 2 at saturation and slightly above, and area 3 in a region just beyond area 2. Plate voltages were 13.5-19 volts. Armstrong, Emeleus and Neill's results may be stated briefly as:

a. The oscillations are stable and reproducible, varying in frequency and magnitude over the tube characteristics.

b. The oscillation frequency agrees with the Langmuir-Tonks formula, and is independent of probe bias.

c. Electrode geometry has no effect on the existence of oscillations, but anode voltage for maximum response depends on probe position.

d. Wavelength varies inversely with gas pressure.

e. There are radial variations in intensity in a cylindrical diode. The axial pattern of oscillations in a conventional diode followed Merrill and Webb closely.

f. The occurrence of an electron transit time phenomenon as part of the mechanism of oscillation is indicated by the fact that, for a tube passing a temperature limited current,

$$\lambda\sqrt{V_T} \cong \text{constant}$$

λ is the oscillation wavelength, V_T is the tube voltage, filament temperature constant.

g. Under optimum conditions, about one percent of the anode circuit input energy was recoverable as heat in a bolometer. The high frequency energy was less.

h. Velocity modulation theory does not check quantitatively.

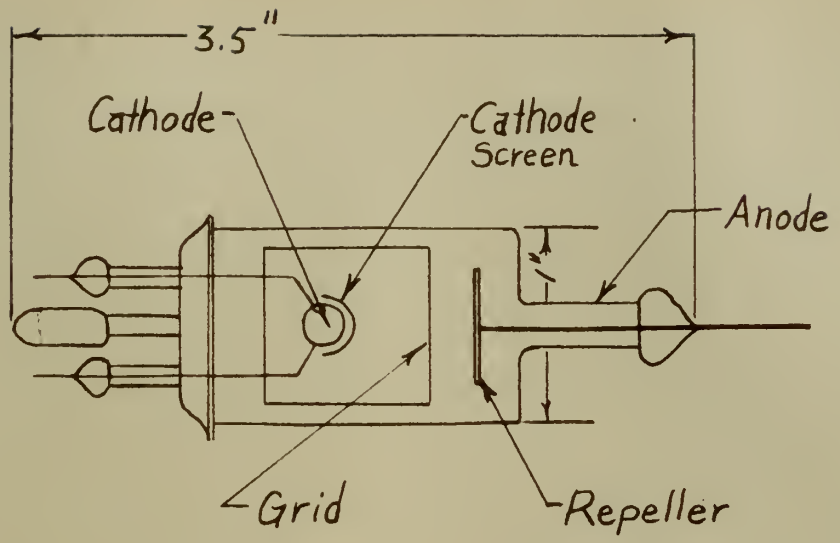


Fig 5. Wehner Sealed Off Plasma Oscillator

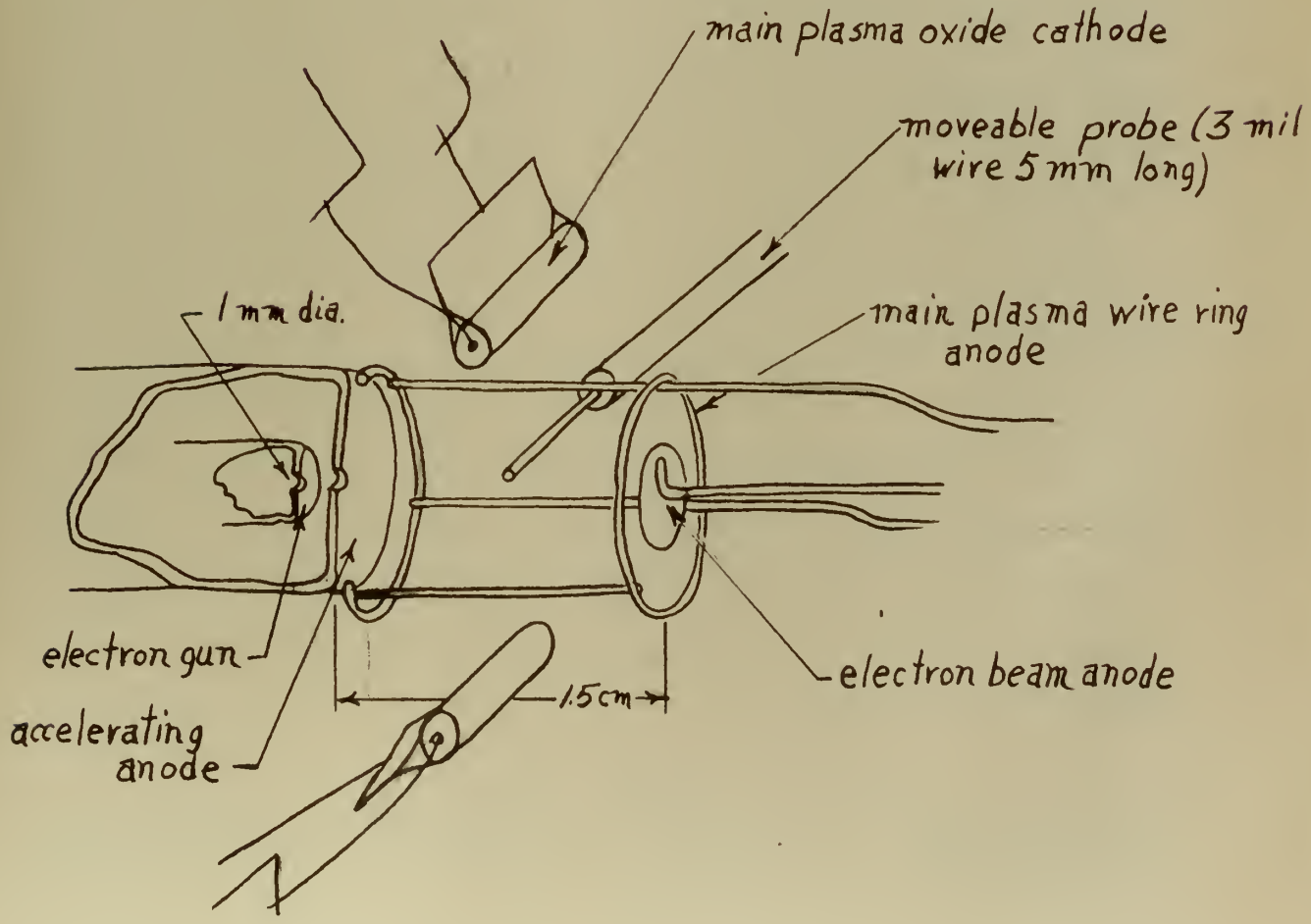


Fig. 6 Electrode Arrangement, Looney & Brown

In 1950 Wehner [11] reported a high frequency oscillator, 800-4000 megacycles, which consisted of a gas cathode with grid, repeller and anode, the first two separated by about a centimeter, in a low pressure (five micron) mercury discharge (Fig. 5). Control of frequency was solely a function of plate current and voltage, with a fixed cathode repeller distance, frequency varying directly with the two parameters. Visible darker layers were observed near grid and repeller ion sheaths, where the electron concentration was such that the observed frequency closely fitted the Langmuir-Tonks equation. Wehner likened operation of the tube to the klystron or reflex klystron, the repeller ion sheath serving as catcher or reflector.

Looney and Brown [12] attacked the problem differently by injecting an electron beam into the discharge plasma, under conditions where the space charge sheaths on the electrodes were closely controllable (Fig. 6). Oscillations were set up at the Langmuir-Tonks frequency and a standing wave pattern was observed with nodes at the bounding sheaths. As the electron density varied, the frequency of oscillation tended to remain constant, shifting discontinuously from one stable value to the next, the standing wave pattern simultaneously shifting an integral number of nodes, still maintaining nodes at each bounding sheath (Fig. 7). Within a greater frequency range, the frequency is a linear function of sheath thickness. Considering Wehner's analysis of the mechanism of oscillations and setting the distance between modulating and energy extraction points of the plasma constant, the relation

$$\lambda\sqrt{V_T} = \text{constant},$$

may be arrived at, in agreement with Emeleus, et al. Energy extraction

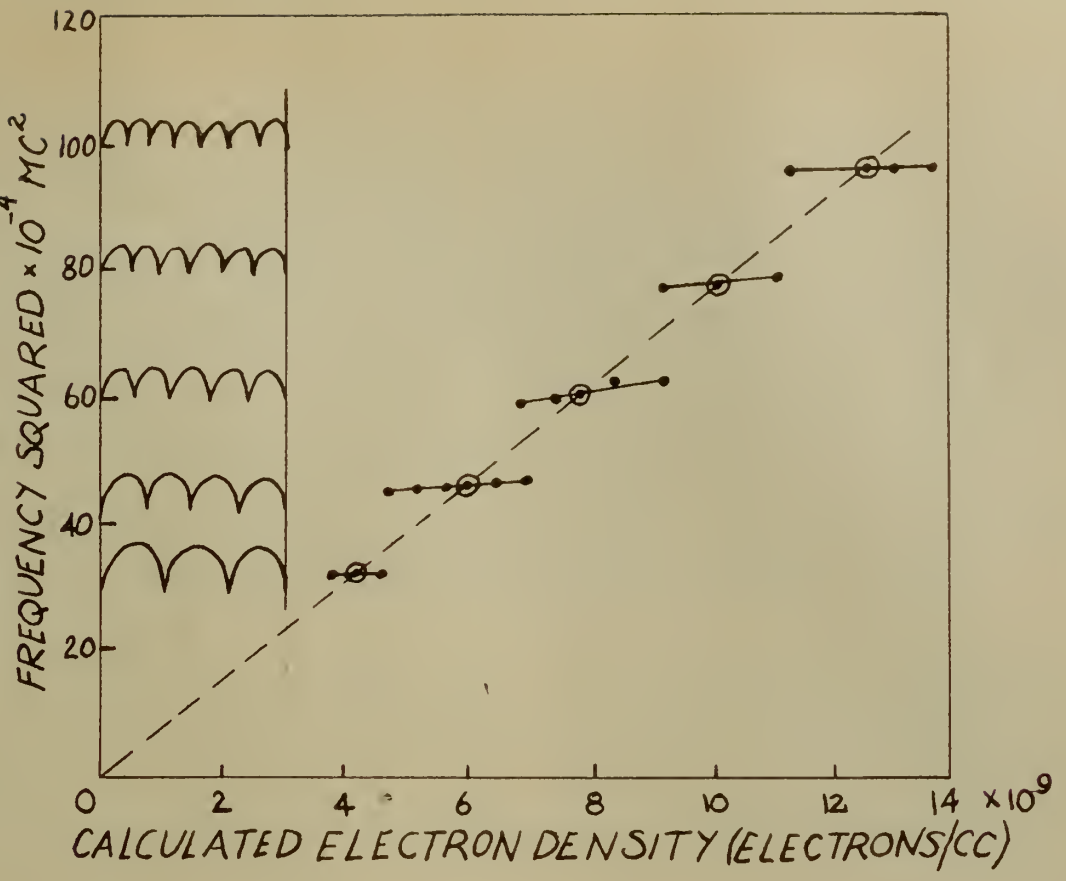


Fig.7 Standing Wave Pattern

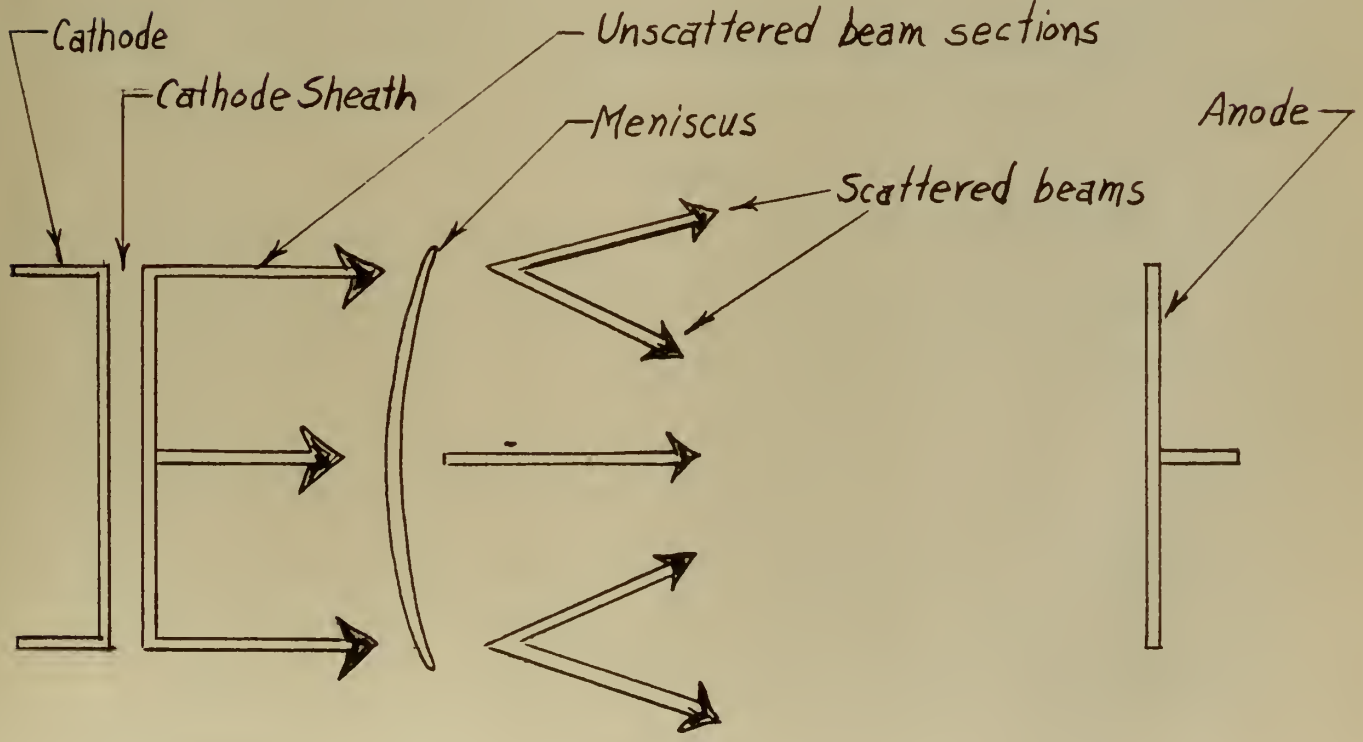


Fig.8 Sections of High Frequency Oscillating Discharge

may take place at any point in the plasma where the field has opposite sign to that at modulating points. This means there must be a node between these two points. Looney and Brown showed that the discontinuous shifts of frequency and standing wave pattern were such as to meet this condition as well as that of Langmuir-Tonks frequency. They proposed that the standing wave demonstrated provided the necessary feedback mechanism to sustain plasma oscillations, and that the oscillations themselves are a type of longitudinal pressure wave set up in the plasma electrons.

In 1955 Allen [13] showed qualitatively that probe analysis is reliable in studying primary electron energy scattering. Previously some doubt had been cast on probe results, which were recorded during plasma oscillations under non-Maxwellian conditions [14]. Allen used spectroscopic analysis to show that primary electron energy scattering occurred in the plasma at the same position and with the same magnitude as that indicated by probe measurements. He found oscillation intensity peaks at various distances from the cathode similar to those found by other workers. He showed that these peaks were caused by electro-magnetic wave feedback to the cathode from the probe and that each peak represents an integral number of beam wavelengths between probe and cathode. Further he showed that under a given set of conditions a disturbance of a particular frequency has constant velocity between probe and cathode, and that this velocity is probably equal to the velocity at the meniscus, of the medium speed group of electrons, which have energies approximately equal to the anode potential.

Allen, Bailey and Emeleus [15] have also reported on the appearance of discharges in mercury and argon, in connection with areas of

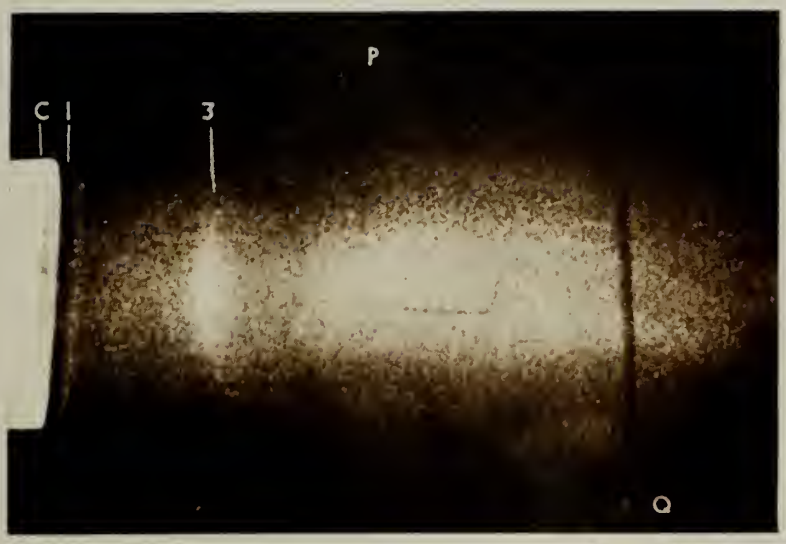


Fig. 9 Cathode sheath (1) and meniscus (3). The anode was just beyond the right-hand edge of the photograph. There is slight convergence visible of the beam to the anode side of (3). The patch of light near the base of the right-hand probe is a reflexion from the tube wall

Fig. 10

Fig. 11

Fig. 10 Beams deviated beyond (3). The convergence of the central beam was often more marked than in this instance. The cathode sheath (1) is clearly visible

Fig. 11 Collapse of ribbon beams at (3). The dark line is a large probe the presence of which was without effect. The cathode shield was at the left-hand edge of the photograph

Fig. 12 Broadening of narrow beam by oscillation. The flat probe is near the right of the photograph. A wire probe, not in use at the time, is behind the flat probe

Fig. 12

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oscillations. Oxide cathodes at a few microns tube pressure were used. They observed a basic discharge structure as follows: a thin dark space charge sheath is found on the cathode. From this sheath, a beam of primary electrons, brighter than the surrounding plasma, proceeds toward the anode. This beam is terminated a few millimeters from the cathode by a bright meniscus, convex to the cathode, which frequently has a dark layer on its anode side. The primary beam splits after passing through the meniscus into approximately conical converging and diverging beams (Fig. 8). Strong plasma oscillations are picked up only in, and toward the anode from, the meniscus. Variation of anode current and pressure moves the meniscus as described by Merrill and Webb [9]. Above a certain current, at constant pressure, the meniscus becomes blurred, several high frequency oscillations not obviously related to one another are detected and noisy low frequency oscillations in the kilocycle to megacycle range appear. An axial magnetic field stabilized this discharge to high currents. Observations of the effect of a probe on the meniscus lead to the conclusions that there is some sort of feedback mechanism from probe to discharge, and that the main growth of scattering occurs in one to two millimeters (Fig. 9,10,11, 12). In addition, simultaneous high frequency and low frequency oscillations were noted in a discharge using a six millimeter flat probe so placed that the electron stream was perpendicular to it when impinging on its surface. The arrangement was roughly similar to that of Looney and Brown [12], and showed similar frequency pulling effects. The existence of transverse effects in the primary beam was shown. The postulated mechanism was that of a slipping stream reaction between primary and plasma electrons, initiating near the cathode and building

catastrophically at the meniscus, thereby generating oscillations of both high and low frequency.

Very recently Boyd, Field and Gould [16] have produced growing waves in a low pressure mercury plasma by modulating an entering electron beam with a slow moving electromagnetic wave, helically propagated. They show that the rate of growth rises sharply to a maximum as plasma frequency approaches excitation frequency and falls monotonically as it recedes. This experiment constitutes the first successful verification of the growing wave theory of Bohm and Gross and others.

4. Theory

A plasma has been described as an essentially neutral body of positive ions and electrons, the response of which to a disturbance is one of regaining the stable or equilibrium state. In such a plasma, an electron is affected by all other particles which surround it and it in turn affects each of those particles. An attempt to derive a theory of plasma oscillations considering the individual effects of each action pair, summed over all pairs, involves such complexity as to be impossible of solution. All theories of such oscillations therefore consider the electron in Hartree's self-consistent field approximation, in which only one electron is considered as a particle, and the effect of the others on it is replaced by their smoothed, averaged space charge and current distritution. The extent to which this approximation is allowable cannot easily be determined mathematically, but experiments have indicated that the interaction is not very much stronger than the theoretical value.

There are two general approaches to the problem of mathematically describing plasma oscillations. The first of these is from the point

of view of regular electron streams, without random motion. Pierce [17], Haeff [18], Bailey [19] and Gabor [20], have derived solutions using this approach. The second attack considers the plasma in complete thermal disorder. Langmuir and Tonks [7], Vlasov [21] and Bohm and Gross [22] and others have derived solutions utilizing this basic assumption.

The theories developed considering electron streams are useful in showing how plasma waves can develop from interactions between ions and the beam or between two or more beams. For the case of a uniform electron cloud at rest, with neutralized charge, Gabor [20] derives the dispersion equation

$$\left(c^2k^2-\omega^2\right)\omega^2\,\vec{s}_o = \omega_p^2\left[c^2\vec{k}\left(\vec{k}\cdot\vec{s}_o\right)-\omega^2\vec{s}_o\right] \qquad (1)$$

by considering particular solutions of the form

$$\vec{s}\,(x,y,z,t) = \vec{s}_o\, e^{j(\vec{k}\cdot\vec{r}-\omega t)}$$

to his self consistent dynamical equations of irrotational electron streams. $\vec{s}$ represents a progressive wave, $\vec{r}$ the radius vector, $\vec{k}$ the wave vector, perpendicular to the phase fronts and pointing in direction of propagation. The scalar value of $\vec{k}$ is $2\pi/\lambda$ and is called the propagation constant. ω is the wave phase frequency.

ω_p is a constant frequency given by

$$\omega_p^2 = \frac{4\pi ne^2}{m}$$

in Gaussian units. (Derivation of this equation is shown on page 19). n is electron density, e is the electronic charge, and m is the mass of the electron. $f_p = \omega_p/2\pi$ is called the "plasma frequency" [23]. The relation between $\vec{k}$ and ω is a function of the angle between $\vec{s}_o$, the stream vector and $\vec{k}$, the propagation vector.

The two cases of interest are:

(1) $\vec{k}$ perpendicular to $\vec{s}_o$ and (2) $\vec{k}$ parallel to $\vec{s}_o$. In case (1), (transverse waves) the dispersion law is $\omega^2 = \omega_p^2 + c^2k^2$. By defining a refractive index $\mu = \omega/ck$, we obtain $\mu^2 = 1 - \frac{\omega_p^2}{\omega^2}$ $(\mu>0)$. This shows that frequencies less than $\omega = \omega_p$ are not propagated in the quiescent plasma. $\omega = \omega_p$ is the critical frequency. Note that a uniform translation does not affect the formula for ω.

For case (2), $\vec{k}$ parallel to $\vec{s}_o$, (longitudinal waves), the dispersion relation reduces to $\omega^2 = \omega_p^2$, or the only possible frequency of longitudinal waves is the plasma frequency, at any wavelength. The group velocity, $Vg = d\omega/dk = 0$, so that the energy of the plasma waves is not propagated if the cloud is at rest. If there is a drift, the oscillations are carried along with the electron stream.

Considering two interacting partial electron streams in the same space, with all velocities in one direction, the dispersion law becomes

$$\frac{\omega_1^2}{(\omega+V_1k)^2} + \frac{\omega_2^2}{(\omega+V_2k)^2} = 1$$

as derived by Pierce [17] and Haeff [18]. Here ω_1, and ω_2 are plasma frequencies of each electron stream, equal to $\left(\frac{4\pi eD}{m}\right)^{1/2}$. D is the charge density = en, and V_1 and V_2 are phase velocities = ω/k.

Haeff [18] investigated this equation and found in certain instances complex roots for $\vec{k}$, indicating real values for ω. Some of these roots stood for solutions which increased exponentially in the drift direction, which he interpreted as explaining the experimentally observed amplification of small signals. This interpretation is open to objection, however [24]. The discrepancy lies in the fact that the dispersion equation does not refer to any boundary conditions and hence

cannot indicate what solutions are physically possible. The dispersion equations above do not consider the effect of a magnetic field.

Bailey [19] considers the effect of a magnetic field in his general theory of plane waves in an ionized gas in the presence of static electric and magnetic fields. By eliminating from his equations the steady state terms, and considering the variables proportional to $e^{i(\omega t - kz)}$, Bailey determines a twelfth degree polynominal whose roots represent the possible waves. Most of these values of k indicate attenuating waves, but for certain values of ω, k has conjugate complex values, indicating a narrow wave group which will grow in space and time. The presence of a magnetic field increases the possibility of wave growth and widens the frequency range in which it may occur.

The initial theory of the plasma in random thermal disorder was that of Tonks and Langmuir [7]. Fast moving electrons were considered to be moving in a (smeared) uniform positive background, created by the slow moving (large mass) positive ions. The average charge is neutral in a plasma, but local electron irregularities cause fields to be set up, attracting electrons to balance excess positive ions. These electrons overshoot the balance position due to momentum and create fields in the opposite directions. This action results in a simple harmonic motion on the part of the electrons. Solution of the differential equation of motion is $\omega_p = \left(\frac{4\pi n e^2}{m}\right)^{1/2}$ (quantities as described above) or, expressed as a frequency, $f = 8980\, n^{1/2}$ cycles per second. This simple theory neglects the effects of thermal motion of the electrons, except as thermal motion initiates the oscillation.

Bohm and Gross [22] developed a theory for plasma oscillations in an unbounded medium of uniform ion density, considering the effects of random thermal motions but neglecting collisions between particles.

Considering the one dimensional case of longitudinal oscillations only, where the amplitudes are small enough so that a linear approximation applies, it is found that long wavelength oscillations of a plasma with Maxwellian electron velocity distribution are characterized by the dispersion relation $\omega^2 = \omega_p + \left(\frac{3kT}{m}\right)\left(\frac{2\pi}{\lambda}\right)^2$ where

K = Boltzmann's constant

T = absolute electron temperature

λ = oscillation wavelength

ω = oscillation frequency

ω_p = plasma frequency

m = mass of the electron

This result agrees with that obtained by Vlasov [21]. When there is no thermal motion, $\omega = \omega_p$, the plasma frequency, and the group velocity is zero, indicating that there is no propagation of the oscillations. In the case of thermal motion there is a continuous frequency spectrum, $\omega \geq \omega_p$ of undamped waves.

In developing the dispersion relation, Bohm and Gross showed how a moving potential wave in the plasma would trap electrons in its trough, causing them to oscillate there while being transported with the wave. Due to differences in velocities, however, the effect of such oscillations may be neglected in considering long wavelength oscillations, as above.

The dispersion relation given describes the steady state oscillations, and requires that initial perturbations in density and velocity meet particular boundary conditions. If the initial perturbations do not satisfy the boundary conditions, oscillations of any frequency are

possible. In time, however, such oscillations of frequencies not given by the dispersion relation get out of phase and damp out, so that only the dispersion frequency is apparent in macroscopic averages. The plasma oscillations can therefore be regarded as a dynamically stable limiting form of motion, about which small deviations due to random motion occur.

Frequencies far from the plasma frequency are supported only by particles moving near potential wave velocity. As the plasma frequency is approached, cumulative and coherent contributions to charge density from all particles serve to build up large potentials, not limited by the number of particles at wave velocity.

The effect of collisions is shown to be to damp the plasma waves, and hence to contribute to plasma stability. The dispersion relation is

$$\omega^2 = \omega_p^2 + \left(\frac{3kT}{m}\right)\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{i\omega_p}{\tau}\right)$$

where τ = mean time between collisions. Unless there are specific excitation processes in the plasma, the oscillations cannot persist.

The existence of specific excitation processes is first shown by considering the effect of the presence of an appreciable number of particles of near wave velocity. The expression for the wavelength of the oscillations, contains a term which may be either positive or negative, indicating excitation or damping. If a special group of high energy particles is present, the expression is positive and excitation occurs. Particles near wave velocity are affected by a field for a relatively long time. Those emerging from a collision with velocities greater than the wave are, on the average, slowed down, losing energy to the wave. Slower particles are speeded up, gaining energy from the

wave. The positive expression referred to above indicates more fast particles than slow ones and a resulting increase in wave energy.

In the case of a plasma of varying density, a wave moving in the direction of decreasing density suffers a decrease in phase velocity. Expressing k as a function of ω, utilizing the equation for plasma frequency,

$$\left(\frac{3KT}{m}\right) k^2 = \omega^2 - \left(\frac{4\pi e^2}{m}\right) n_o(x), \qquad n_o(x) = \text{plasma density.}$$

As $n_o(x)$ decreases, k increases or the wavelength, $\lambda = 2\pi/k$, and phase velocity, $V_p h = \omega/k$ both decrease. If the decrease is slow, trapped electrons will be slowed down continuously, losing a maximum of energy to the wave, until thermal velocity is reached, where the mechanism fails. Conversely, trapped electrons may be accelerated, a possible mechanism for cosmic particle acceleration.

Finally, the presence of electron beams of well defined velocity causes instability of the plasma, with resulting amplification of small oscillations until limited by non linear effects. Beams of large velocity spread bunch at different points, so that amplification and instability are reduced. Special groups of particles may be said to create the oscillations which scatter them, since the plasma can modulate more efficiently under conditions of coherent oscillation.

5. Equipment

The equipment used in this experiment consisted of four main components as follows:

(1) Gaseous discharge tube, in which the oscillations were produced.

(2) D.C. circuits for the control of the discharge conditions.

(3) High frequency detection equipment.

(4) Vacuum system for the evacuation and filling of the tube.

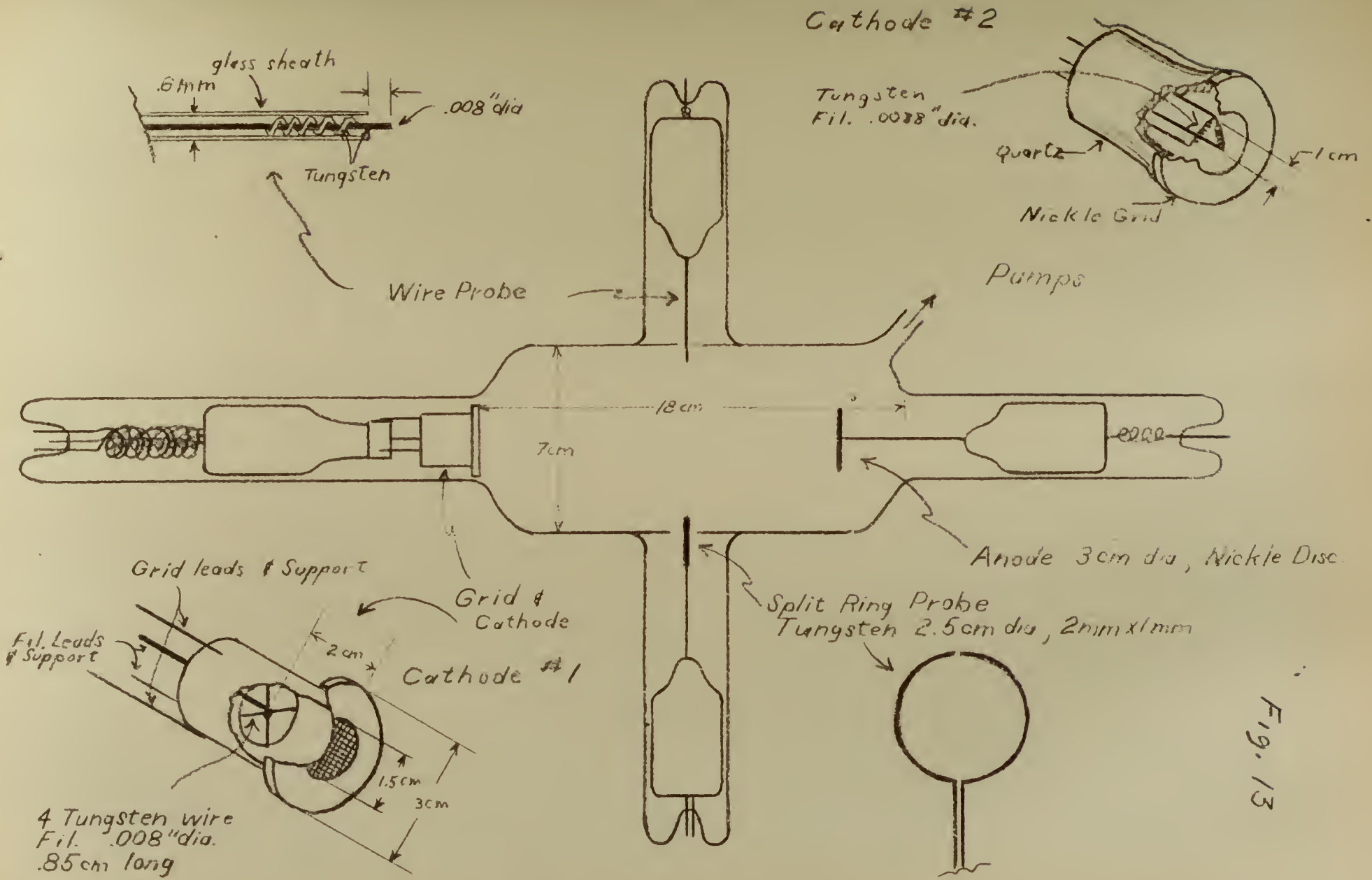


Fig. 13

THE LAZY ELECTRON TUBE

a. Discharge Tube. Fig. 13 is a detailed drawing of the tube used in this work. It was constructed at Stanford Research Institute, Palo Alto, California. In as much as previous workers in the field of plasma oscillations have gathered considerable data using various tube designs, it was considered necessary that the tube be flexible enough so that verification of previous data would be possible. In addition, it was hoped that some new characteristics of the oscillations might be observed. Allen [13] recommended larger disc electrodes for cathode and plate and also a cathode of rugged design which would withstand ion bombardment at high plate voltages. It was decided that a standard wire probe and a split ring probe should be used for probing the plasma. All of these design requirements were built into the tube. In addition, a control grid was introduced to allow further flexibility in discharge conditions.

The cathode arrangement is a Gabor type gas cathode [25]. This is a cathode where the discharge beam electrons are produced in an almost field free region. In this case, the field free region was produced by enclosing the tungsten filaments in a nickel cylinder with a screened opening at one end for the emission of the beam, and a ceramic disc closure at the other end. The filaments were designed for a maximum of one volt drop heating current so that a minimum of field would be produced inside of the grid, which covered the filaments. This arrangement also gave additional control over the discharge by allowing variation of the grid potential with respect to the filament.

A second cathode arrangement also used was designed along more conventional lines. It consisted of two coiled tungsten filaments which could be operated separately or in series, with a voltage drop of approximately 9v across each element. The filaments were enclosed in a

quartz cylinder with a nickel ring around the emission end which could be employed as a grid.

The tungsten wire probe was patterned after a design recommended by Wehner and Medicus [26]. The split ring probe is an attempt to design a probe which would be capable of detecting oscillations with the minimum disturbance to the discharge, while also being capable of distinguishing between different lateral modes of oscillation. This probe could be rotated so that the plane of the ring could be placed either perpendicular or parallel to the discharge beam.

All electrodes in the discharge tube were attached to soft iron cylindrical cores sealed in glass. These provided for movement of the electrodes with magnets. The grid to plate distance could be varied from zero to eight centimeters. The electrode spacing was accurately measured by the use of a travelling telescope, which was accurate to + .0025 mm.

b. D.C. Circuits. The circuits used for control of the discharge and probe biasing are shown in Fig. 14. The main D.C. power used for the tube potential was obtained from a voltage regulated power supply manufactured by Kepco Laboratories, Model 1250B. Power was available at zero to one thousand volts, at zero to five hundred milliamperes, regulated to less than 3 millivolts RMS.
Nickel - Cadmium batteries were used for the filament heating, and "B" batteries for the grid and probe biasing.

All D. C. circuits were wired through a central control panel to allow rapid changing of meter scales, and reversing of polarities, in the case of the grid and probe bias. All voltmeters and ammeters were capable of being shunted or opened so that independent and accurate measurements could be made.

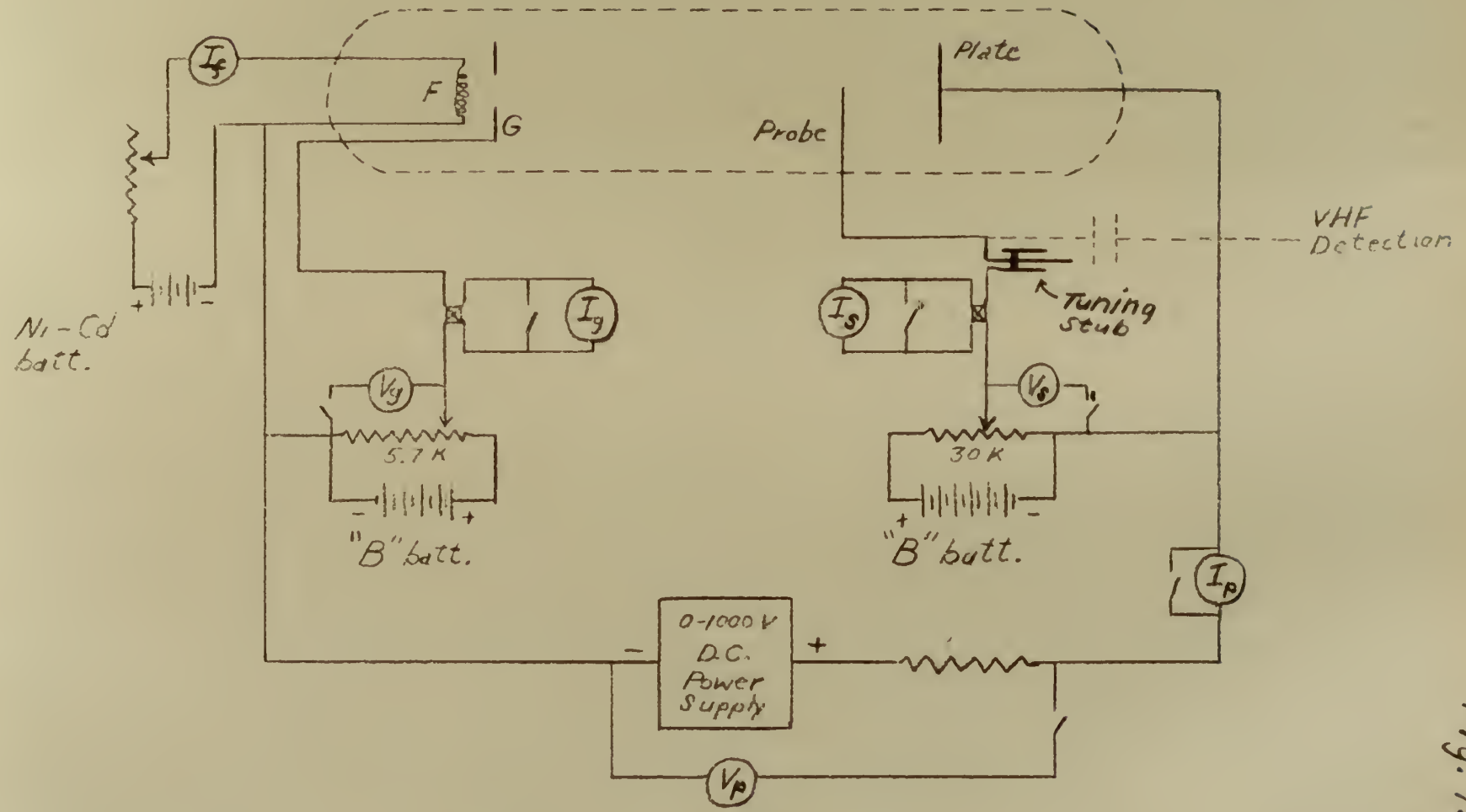


Fig. 14

DC Circuits

c. High Frequency Detection Equipment. The high frequency detection equipment consisted of a superheterodyne frequency meter TS-186D/UP with built in crystal calibration. This meter determines the unknown frequency by comparing it with a known frequency, indicated by a null reading on a sensitive VTVM. The accuracy of the meter was within .01%, with a sensitivity of 0.5 millivolts, and a range from 100 - 10,000 megacycles.

In addition a Hewlett-Packard Model 150A oscilloscope was used ac across the tube for detection of lower frequencies.

d. Vacuum System. The vacuum system used was patterned after the ultra-vacuum system described by Alpert [27]. Vacuums on the order of 10^{-10} mm of mercury are easily obtainable with this glass system. The principle features of this system are the Alpert ion gauge, and the use of metal valves in lieu of stopcocks. The use of metal valves removes one of the major limiting factors of high vacuum. The Alpert ion gauge, which minimizes the residual collector current due to soft x-rays, makes possible the measurement of ultra-vacuums. Also, the ion gauge was used as a pump below the minimum pressures of the oil diffusion pump. A schematic diagram of the vacuum system is shown in Fig. 15.

Baking out of the system, which is always required for these ultra-vacuums, was accomplished by placing a portable electric oven over the entire system, except for the oil diffusion and fore-pumps.

In as much as plasma oscillations occur at gas pressures of 10^{-3}mm of mercury, it was necessary to find a gauge which was capable of accurate measurement of pressures in this range and which would not contribute any contamination to the system. Solution of this problem was first

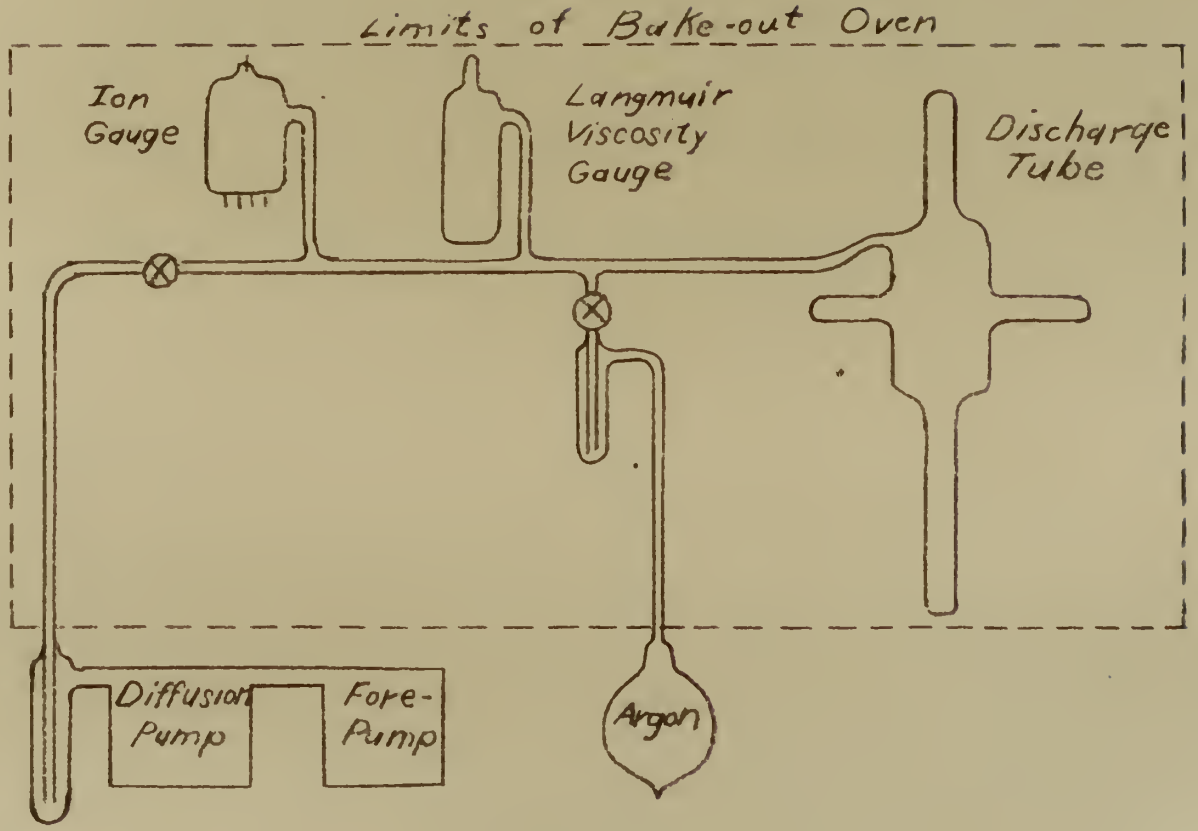


Fig. 15

Schematic of Vacum System

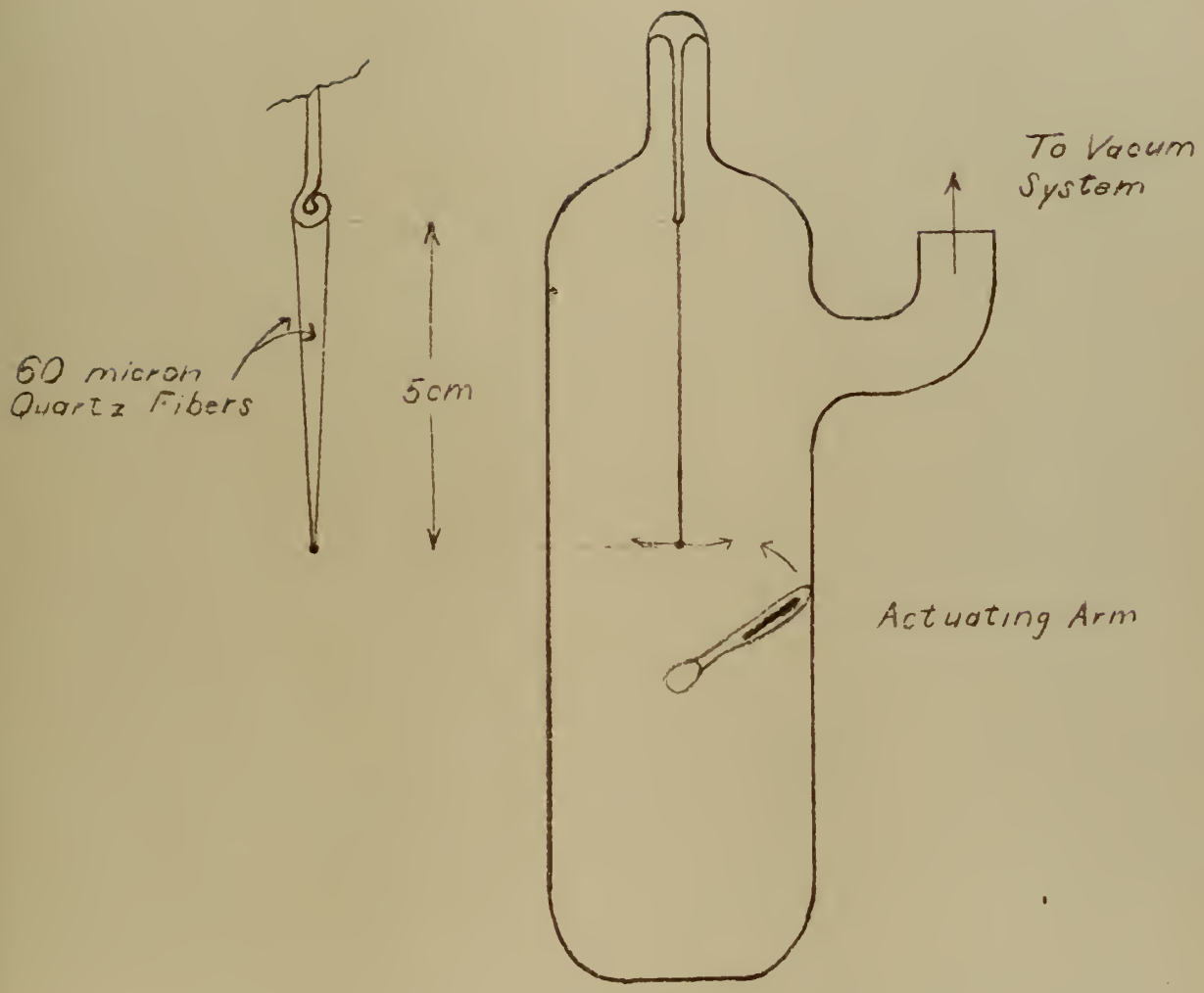
attempted by using a Pirani gauge, which had been carefully calibrated and which had a flashing circuit for filament cleaning, so that the pressure indications would be stabilized to the absolute calibration. Flashing was accomplished by introducing 10-15 volts AC across the filaments, which raised their temperature to approximately 900°C and removed any heat transfer contaminants. Although this procedure increased the reliability of the pressure indications, it still did not produce readings which were sufficiently reproducible.

It was next decided that the Alpert ion gauge might be calibrated to extend into the micron range, in as much as it utilizes an irridium filament which is not damaged even when operated at atmospheric pressures. This approach was not successful due to non-linearities of the gauge in the micron range.

It then became apparent that there was no commonly used pressure gauge for the micron range, with the one exception of the McLeod mercury gauge, which was ruled out due to mercury contamination. On a suggestion of Dr. Cleson, a Langmuir viscosity gauge [28] was constructed, a diagram of which is shown in Fig. 14. Although this instrument is not new, it has solved a rather perplexing problem; therefore a few comments on its operation will be made.

It will be noted from the diagram that the gauge is a simple quartz fiber in a vertical suspension. By means of a magnet, a glass arm with metal core is used to set the fiber in vibration. Langmuir found that in the range 10^{-2} to 10^{-5} mm of mercury, the time required for the amplitude of the oscillating fiber to decrease by one-half was linearly related to the pressure of the surrounding gas.

Fig. 16



LANGMUIR VISCOSITY GAUGE

This relationship is as follows:

$$P\sqrt{M} = \frac{a}{t} - b$$

where P = pressure

M = molecular weight of gas

t = time for amplitude to decrease one-half

a, b = constants

The values of a and b must be determined by calibration with an absolute gauge such as the McLeod gauge. Results of such calibration are shown in Fig. 17. Measurements were made using argon, neon and helium. Due to the extremely sensitive nature of this instrument, variations in atmospheric water vapor content resulted in definite changes in pressure indications. Therefore data which was taken on air were not standardized, and are not reported herein. The dotted lines shown on the calibration graph are the expected values as predicted by the above equation. It will be noted that excellent agreement has been obtained for argon and neon. For helium, the results indicate the presence of a gas of larger molecular weight than that of helium. This was the case, in as much as the vacuum system on which this data was taken was not cleaned of all residual gases. It should also be noted that the upper limit of linearity is approximately 30-70 microns, depending on the gas used.

Photographs of the discharge tube and overall system are shown in Figs. 18 and 19.

6. Vacuum System Operation

With the exception of the metal valves and ultimate vacuum, the system was operated along conventional lines. After repair of any large leaks, the system was pumped down to 10^{-5} millimeters of mercury

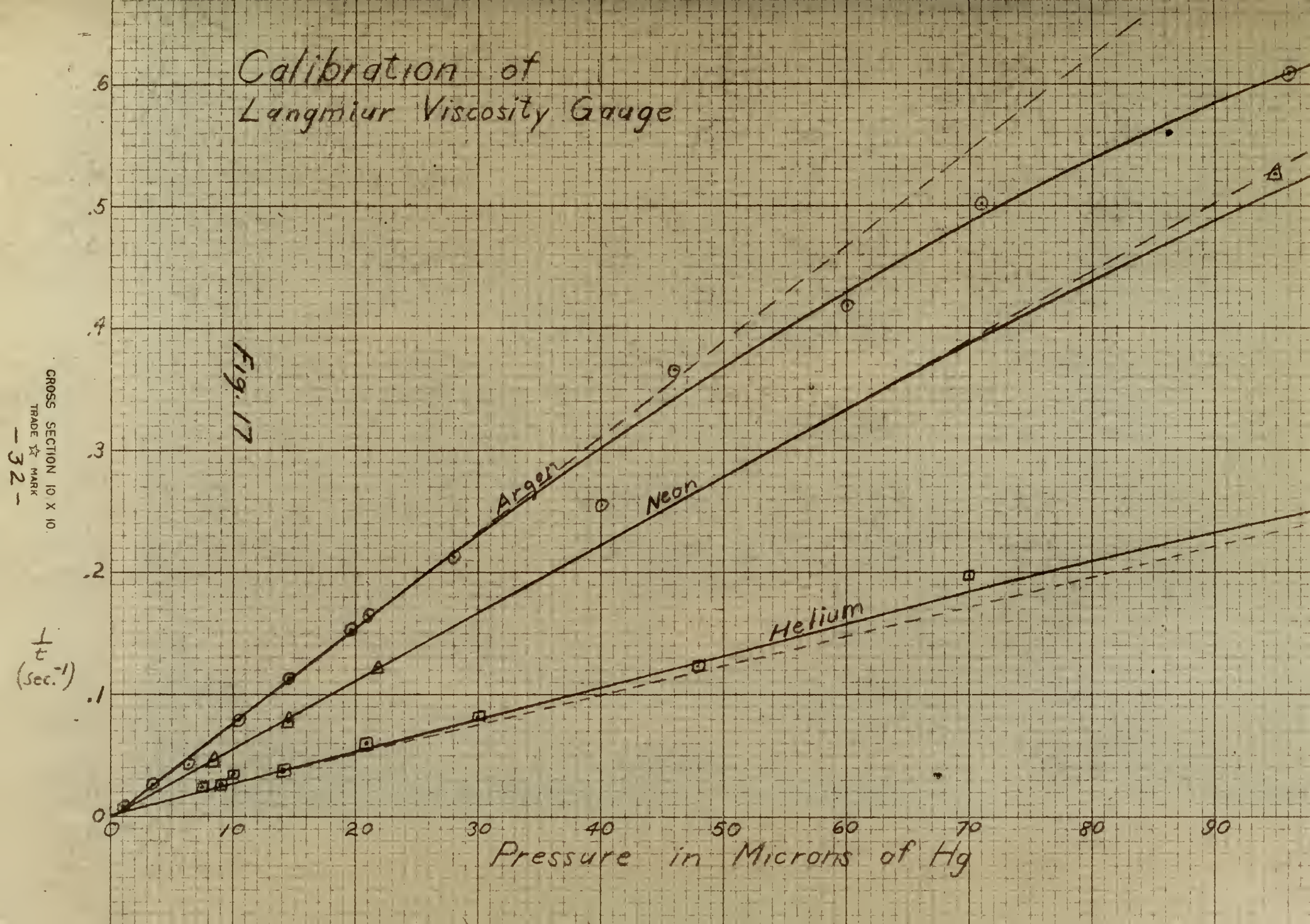


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Fig. 18 Experimental Tube

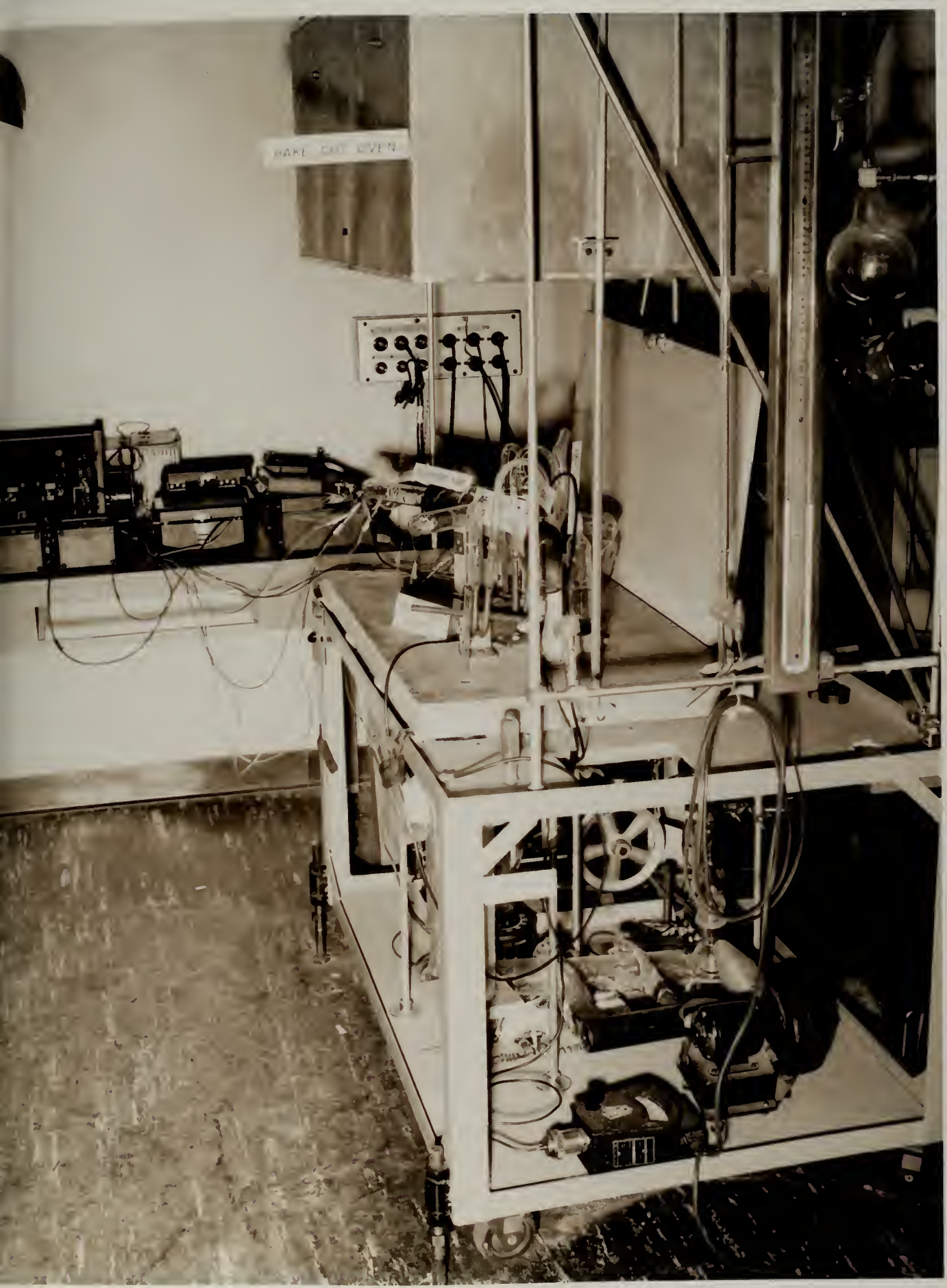

Fig. 19 General Experimental Arrangement

pressure in six to twelve hours (the range at which absorbed gases usually limit any further decrease in pressure, except after prolonged pumping or bakeout). The bakeout oven was then lowered over the system and the temperature raised to 450° C for four to six hours, followed by slow cooling with the oven in place but turned off. About six to eight hours was required to cool to room temperature. The ion gauge was then outgassed for one-half to three quarters of an hour, followed by system pump down to the diffusion pump ultimate, 5×10^{-8} millimeters. At this time, the isolation valve was closed so that the ion gauge could complete pumping down to the ultimate vacuum. In about two to three hours, pressures of 5×10^{-9} millimeters were reached, and very little further decrease in pressure could be obtained, when the volume of the system was three to four liters. On previous occasions, pressures of 5×10^{-10} millimeters were obtained on the same system with a system volume of six tenths of a liter.

Leaks were detected with a Tesla coil prior to diffusion pump operation, and with a sensitive bridge circuit and Pirani gauge for lower pressures and leaks in and around metal fittings. Both of these methods are commonly used and will not be discussed here; however, it should be noted that the Pirani gauge method was found to be capable of detecting leaks as small as 5×10^{-5} liters per second.

Certain precautions are necessary for effective operation of the metal valves. During bake-out the driver mechanism is always removed and the valve held in an open position with a bracket and screw. This prevents the screw threads from becoming frozen in one position during bake-out. Caution must also be used when opening a valve, so that the diaphragm is not ruptured by opening too far. If the valve is opened no more than one turn after the valve is free to turn by hand, the

possibility of over opening is prevented. Two valves were accidentally exposed to atmospheric air during bake-out when a break in the glass tubing occurred. The exposure oxidized the valve interiors and rendered them useless due to their high internal conductance, even when they were seated with twice the recommended torque (20 ft-lbs.). Of the two valves described by Alpert [27], the differential drive type proved far superior, because less torque is applied to the diaphragm, and metering of gas can be controlled to a finer degree.

After the ultimate pressure of 5×10^{-9} millimeters of mercury was obtained, the line to the spectroscopically pure argon bottle was closed and the electrodes were degassed by use of an induction heater. When the pressure rise due to degassing was above the diffusion pump ultimate (10^{-8}) the isolation valve was opened for continuous pumping during the remaining degassing procedure. Filaments were also operated at maximum rating ($2500^{\circ}K$) using 4.4 amperes heating current for approximately two hours. The system was then pumped down to 3×10^{-7} millimeters, ready for gas filling. The spectroscopic argon was metered into the system through the liquid air trap until a pressure of two millimeters was obtained. This procedure was repeated again after pumping down so as to give a flushing action. The tube was then filled to a pressure of 10^{-3} millimeters, ready for gaseous discharge operation.

It is estimated that the above procedures resulted in a contamination of less than one part in 10^{12}. No further sources of contamination, such as stopcocks, were present, except for minute quantities from the electrodes.

7. Results

The work with the first cathode, employing five straight filaments in parallel, was not successful. Presence of the metal cylinder and screen wire surrounding the filament caused the electrons to be trapped inside, with the result that the emission current was too small to give measurable oscillations. Removal of the wire screen improved emission, but not enough. The large heating current necessary also contributed to the fragility of the design, for in case of single filament failure, the other filaments were required to carry a heavy overload. It was concluded that operation under such extreme conditions, while desirable from the standpoint of reducing the voltage gradient in the cathode, was not feasible.

The work with the second cathode, which was of more conventional design, was successful. Effort was aimed at detecting plasma oscillations in connection with plotting a plate voltage versus current curve, so that the oscillations could be located along the characteristic, as in the work of Armstrong and Emeleus, and Neill and Emeleus [10]. Tube parameters and conditions of operation applying to the figures are given below.

Tube parameters:

Plate to grid separation	18.76 millimeters
Filament heating current	4 amperes 2000° K
Grid voltage (w.r.t. negative filament)	-1.0 volts
Probe voltage (w.r.t. plate)	0 volts

Operating conditions:

a. Figure 20

Pressure	6.4 microns
Temperature (Room)	26.9°C

No probes in discharge

b. Figure 21

Pressure	3.1 microns
Temperature (Room)	27°C
Ring probe to grid separation (from grid to cathode side of ring probe)	0.92 millimeters

c. Figure 22

Pressure	6.4 microns
Temperature (Room)	26.9°C
Ring probe to grid separtion	2.01 millimeters

d. Figure 23

Pressure	6.4 microns
Temperature (Room)	26.9°C
Ring probe to grid separation	4.03 millimeters

The oscillations observed are shown in each figure. The lower frequencies, which were observed on an oscilloscope connected across the negative filament and plate leads, are shown on the left hand side of the characteristic curve, with peak to peak voltage shown in parenthesis after each frequency. High frequency oscillations, which are believed to be associated with plasma oscillations, are recorded on the right hand side of the characteristic curves, with relative intensities in parenthesis. The plasma oscillations were detected using the ring probe and frequency meter. A tunable stub in the probe circuit was used to differentiate between harmonics and find the approximate wavelength. By tuning the stub, the impedance to the high frequency signal, in the direction of the probe biasing circuit, was changed, decreasing the signal to the frequency meter at half wavelength points and increasing it at quarter wavelength points. [See figure 14]

Fig. 20 Tube Characteristic & Frequencies, Probes Withdrawn

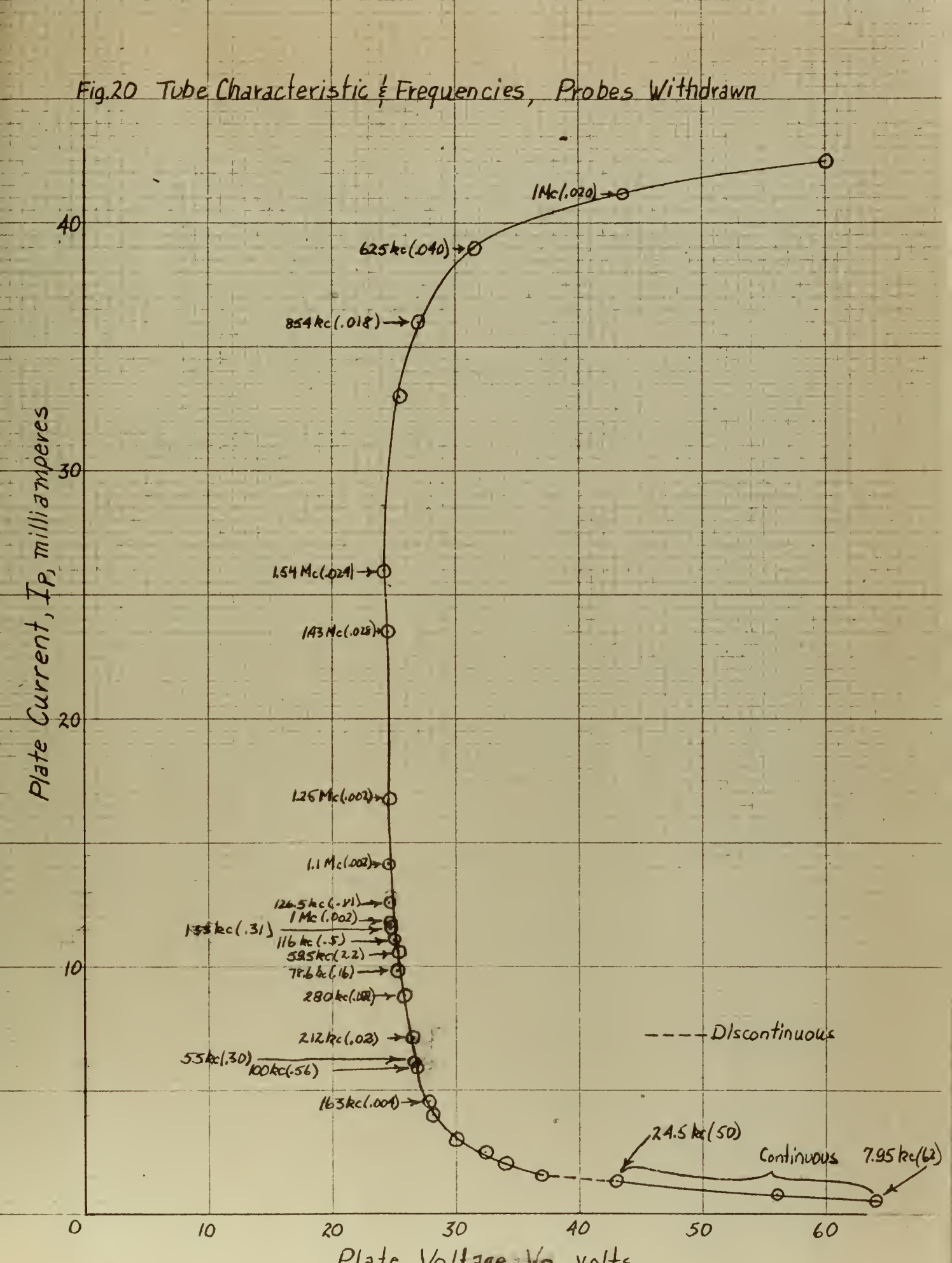

Fig. 21 Tube Characteristic & Frequencies (Ring Probe at 0.92 mm)

Pressure 3.1 μ

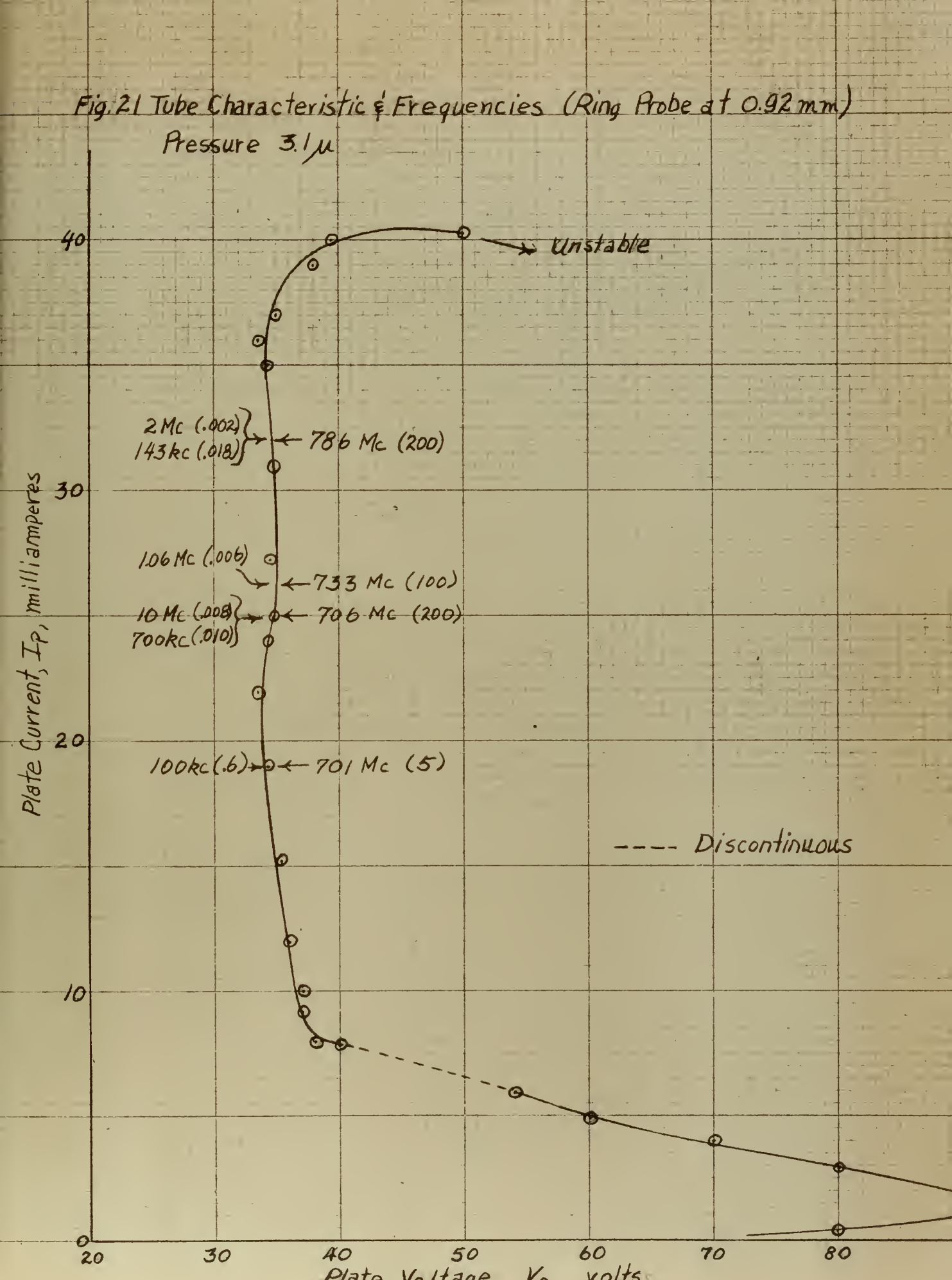

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Fig 22 Tube Characteristic & Frequencies (Ring Probe at 2.01 m m)
Pressure 6.4 μ

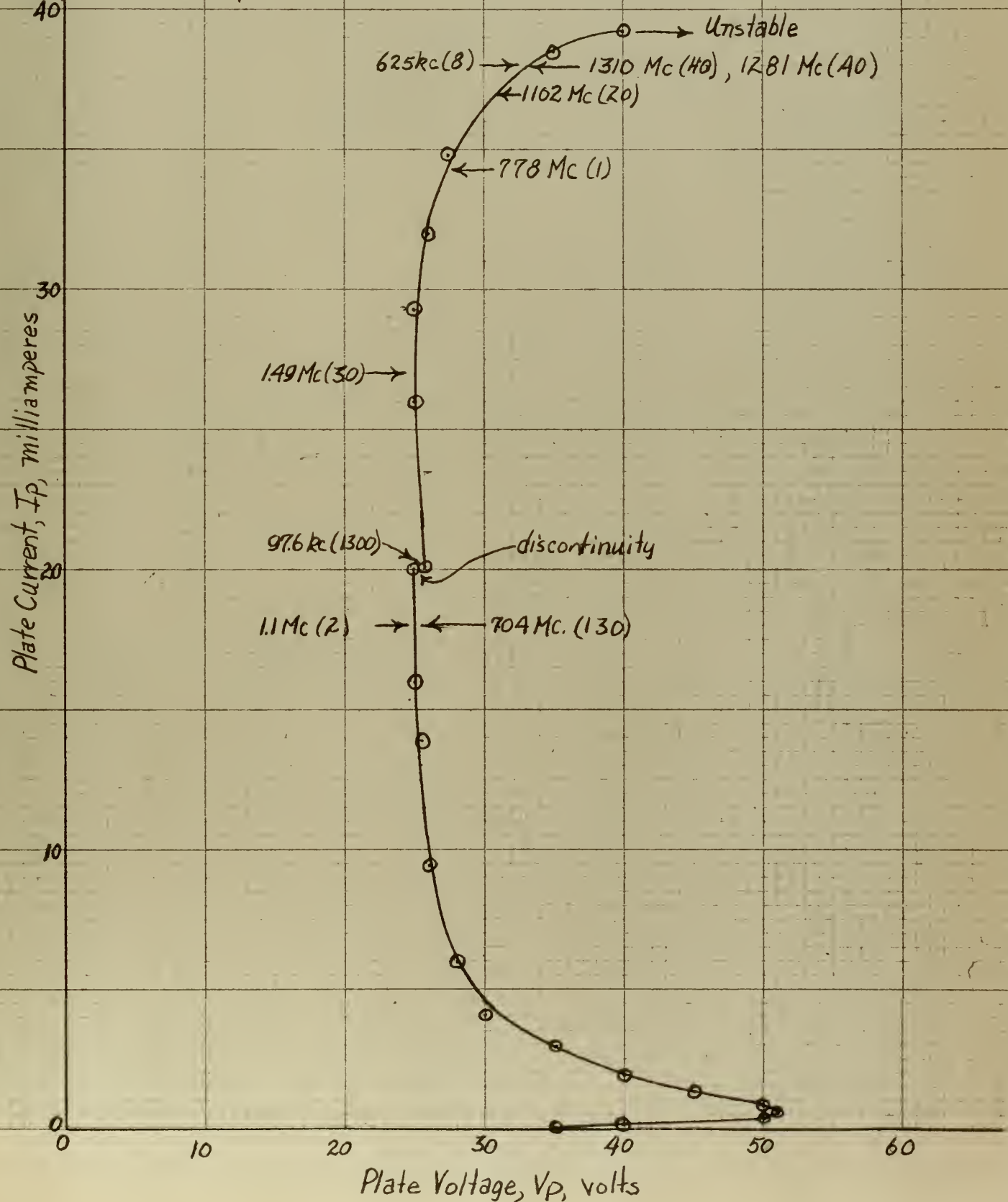
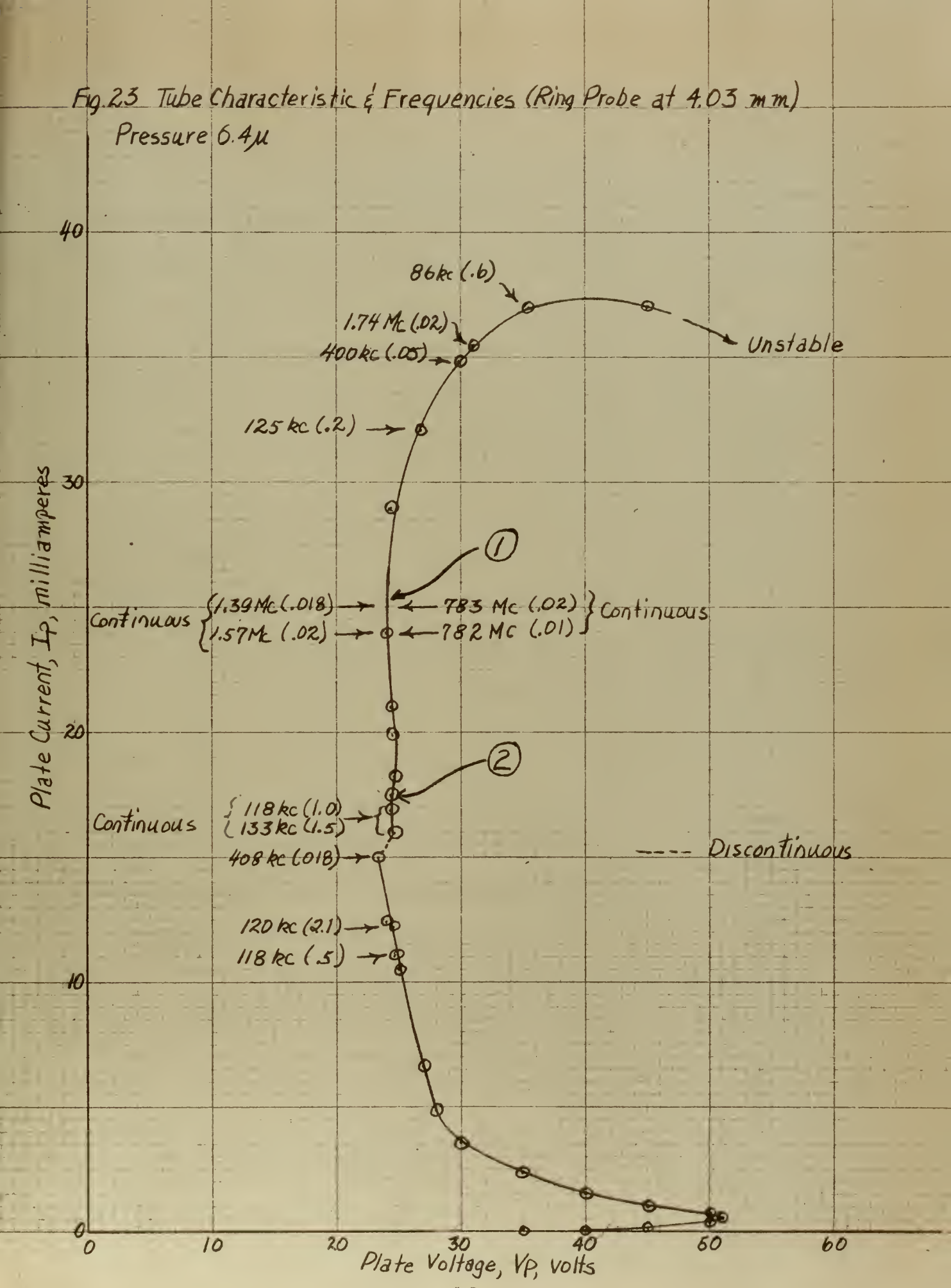


Fig. 23 Tube Characteristic & Frequencies (Ring Probe at 4.03 m m)
Pressure 6.4 μ



Frequencies reported on these characteristic curves should not be interpreted to mean that oscillation did not occur at other points along the curve. It was early recognized that the probe wiring arrangement in the tube produced a large attenuation to high frequencies, making it possible to obtain no oscillation indication from the frequency meter when oscillations of low intensity might actually be present.

A sample probe characteristic analysis was made under slightly different conditions than reported above, using the method of Langmuir and Mott-Smith [2]. By applying the electron density found in this analysis to the Langmuir-Tonks plasma frequency equation [7], a frequency of 580 megacycles per second was predicted. Thus the oscillations reported in this thesis appear to be of the correct order of magnitude.

When the corresponding positive ion density is applied to a similar equation for positive ions, a frequency of two megacycles per second is obtained, indicating that the lower frequency oscillations reported herein can be associated with positive ion oscillations.

The data above was taken with the two halves of the split ring probe connected together. When only one half of the ring was used for detection, grounding the other half through the probe biasing circuit, the intensities decreased by about one-half.

In order to establish that high energy scattering was occurring, probe characteristic curves were recorded at points where high and low freuqency oscillations were occurring simultaneously, and also at points where no oscillations could be detected. Fig. 24, (a), (b) and (c) show the results of such measurements.

Fig. 24 Wire Probe Characteristics

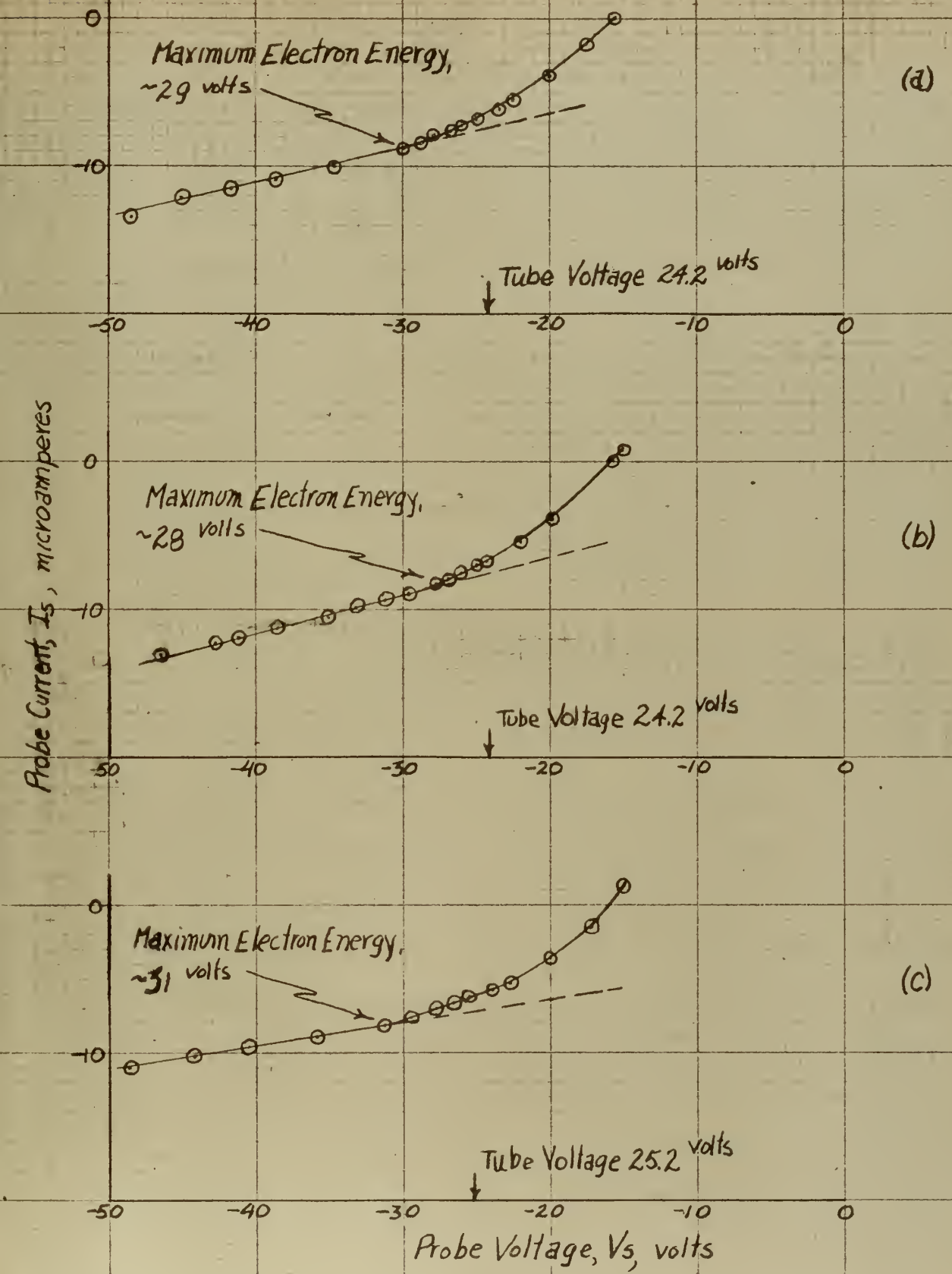


Fig. 24, (a) and (b) were both taken at the point marked (1) in Fig. 23 when plasma oscillations and positive ion oscillations were occurring simultaneously. Fig. 24 (c) was recorded at point (2) in Fig. 23 where no oscilation could be detected. Fig. 24, (a) and (b) demonstrates the reproducibility of the characteristic when probe cleaning is used immediately prior to taking data. All three characteristics indicate that there are present in the discharge electrons with energies approximately 4-5 volts greater than the cathode-plate potential, considering the grid potential, which was -0.90 volts with respect to the negative filament lead. This indicates that high energy scattering, which has been associated with plasma oscillation, was occurring even though the high frequency detection equipment failed to detect any oscillations in case (c) above.

Probe characteristics recorded without prior cleaning of the probe resulted in completely erratic results, showing that cleaning of the probe was necessary. The probe was cleaned of absorbed argon by applying a positive voltage to the probe sufficient to draw two to three milliamperes of current, which heated the probe to cherry red.

Fig. 25, (a) and (b), shows typical waveforms of the lower frequency oscillations. In part (a), 1 and 2 are the beginning of a band of continuous frequency, and 3 (Upper and lower) are the end of that band. The extent of frequency pulling is seen to be 5.8 kilocycles.

The pairs of traces in part (b) show individual frequencies encountered as the applied voltage was increased. In these cases, each frequency is discrete and there is no appreciable frequency pulling.

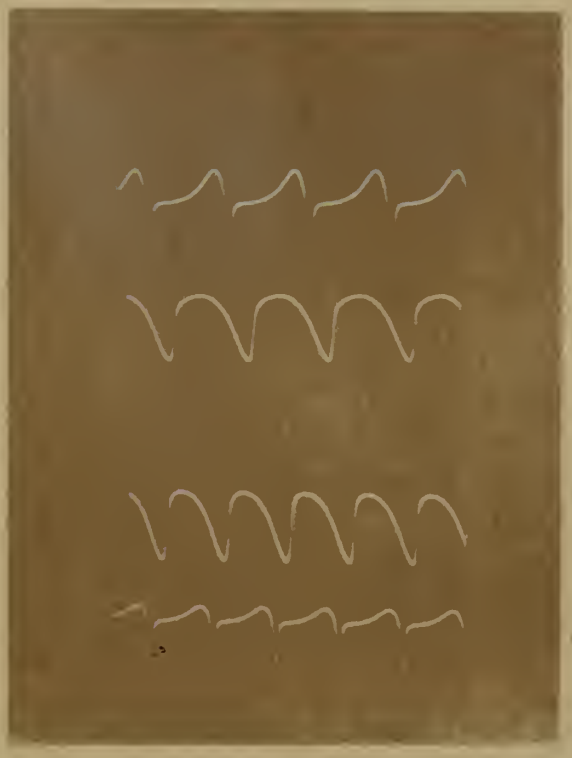
Data for the traces is tabulated below

Photo	Part	V_p volts	V_g volts	Anplitude volts, peak to peak	Freq.	Scope Connection
a	1	49	-5	0.64	20.5 kc	Grid to fil. neg.
a	2	49	-5	40.0	20.5 kc	Plate to fil.neg.
a	3 upper	47	-5	44.0	26.3 kc	Plate to fil.neg.
a	3 lower	47	-5	0.9	26.3 kc	Grid to fil.neg.
b	1 upper	27	-5	0.4	145 kc	Plate to fil.neg
b	1 lower	27	-5	0.03	145 kc	Grid to fil.neg.
b	2 upper	26	-5	1.75	98 kc	Plate to fil.neg.
b	2 lower	26	-5	0.19	98 kc	Grid to fil.neg.
b	3 upper	26	-5	.075	1.6 Mc	Plate to fil.neg.
b	3 lower	26	-5	.020	1.6 Mc	Grid to fil.neg.

8. Conclusions

The primary objective of this work was to place in operation a discharge tube in which plasma oscillation could be observed. As evidenced by the high frequencies detected (700-1300 megacylces per second) and the high energy scattering, it is believed that plasma oscillations were generated.

Failure to detect more plasma oscillations on the characteristic curve is attributed to the high attenuation characteristics of the probe lead wires. The presence of the metal cores for probe movements and the coiled probe leads necessary for probe movement undoubtedly were the chief offenders.



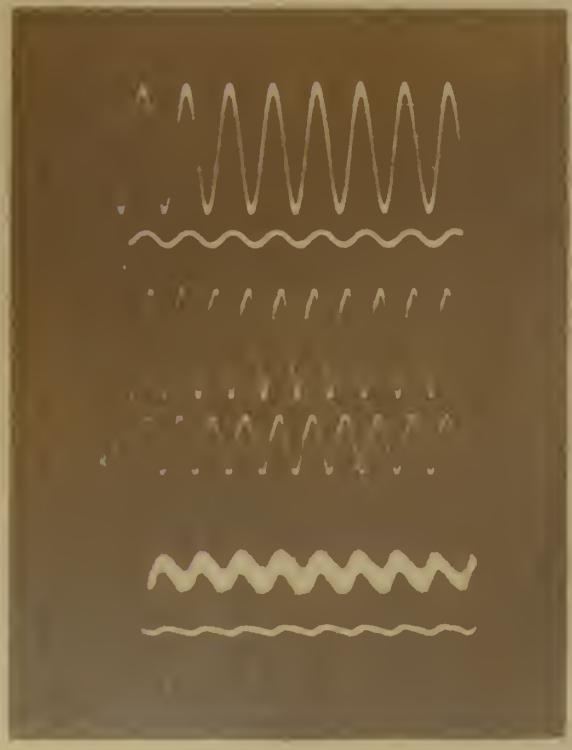


Fig. 25 Typical Lower Frequency Oscillations

By comparison with data obtained by Emeleus, et al, [10] a sample of which is shown in Fig. 26, it can be concluded that the plasma oscillations observed in this work correspond to those found by Emeleus in the region marked (1).

With two exceptions, plasma oscillations detected were observed simultaneously with lower positive ion oscillations. Here is might be concluded that there is a relationship between the two. Certainly, if the two types of oscillations are occurring in the same plasma there must be a relationship. This idea is further strengthened by the fact that it was observed that the amplitude and, in some cases, the stability of the low frequency oscillations were diminished when high frequency energy was removed through the frequency meter, and also when the tuning stub in the probe bias circuit was set at a low impedance point.

Allen [13] hypothesized a feedback mechanism from the detecting probe as a means of explaining the oscillation intensity peaks normally obtained as the probe is moved longitudinally along the discharge. Electromagnetic radiation from probe to cathode was the basis of the mechanism. He determined that the velocity of the oscillation through the discharge was approximately 2.1×10^8 centimeters per second. Using this figure and a frequency of 700 megacycles per second, the wavelength of the disturbance would be three milimeters. The width of the ring probe was measured accurately and found to be 2.78 millimeters. This means that the probe covered nine-tenths of the disturbance pattern, if a longitudinal electron density variation is assumed as the mode of the plasma oscillations. This undoubtedly was another contributing factor in high frequency attentuation.

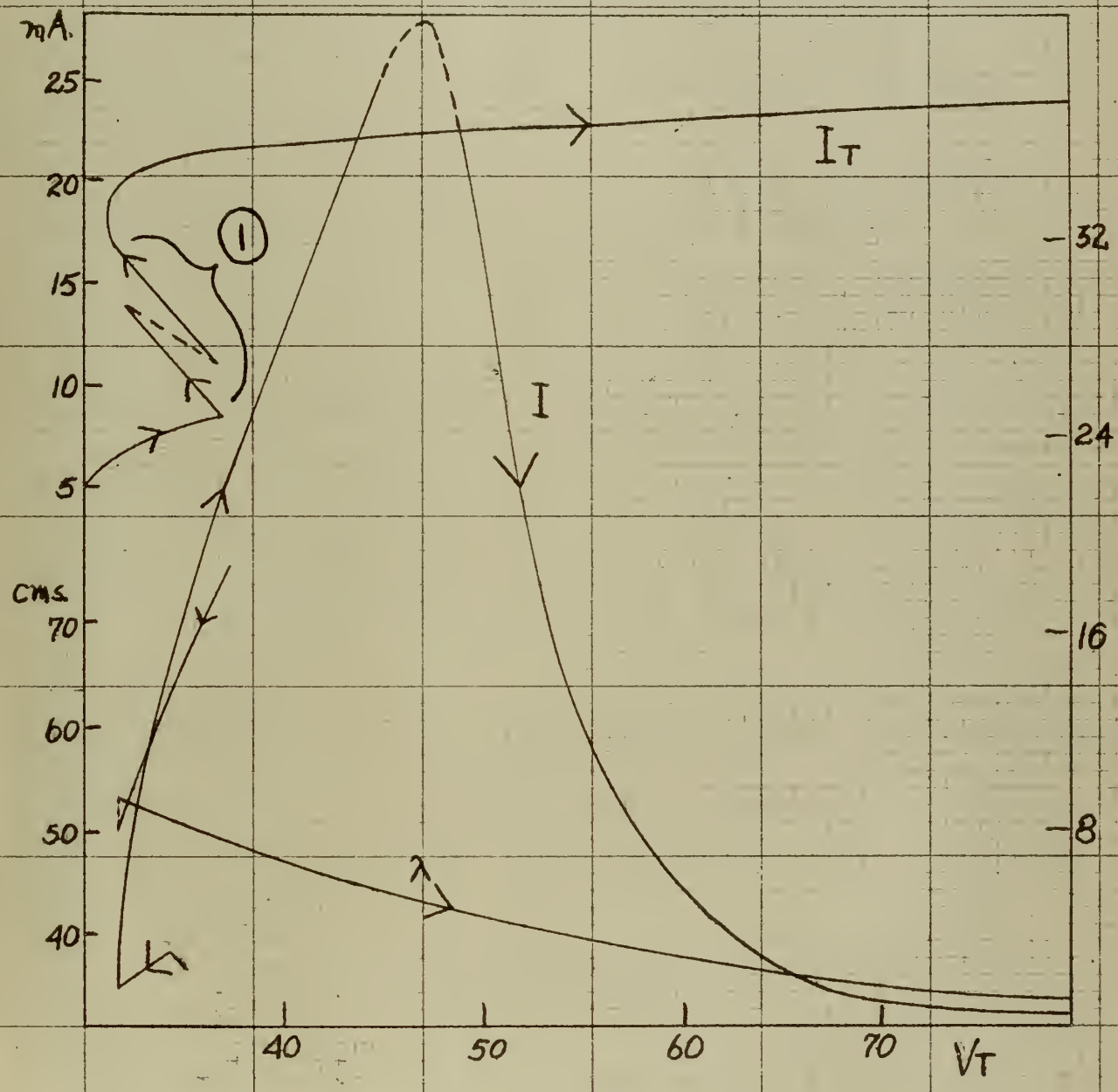


Fig. 26 Tube Characteristic, Neill & Emeleus

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The decrease in plasma oscillation intensity which was observed when only half of the split ring probe was used is compatible with the travelling density variation model of plasma oscillations as well as the model in which the plasma electrons are pulsating in a direction radial to the discharge axis.

9. Recommendations for further work

a. In view of the high frequency attenuation characteristics, probe lead wires in the existing tube should be shortened.

b. The split ring probe should be replaced with a continuous wire loop, of small wire diameter but the same loop diameter (2.5 centimeters). The support and lead from the ring should be connected to the top or bottom of the ring. This will allow tilting of the ring tranverse to the discharge so that space-time phase relationship can be obtained similar to that of a travelling wave antenna.

c. Conduct an investigation into the effect on oscillations of varying grid bias. (The grid was originally intended to be the origin of the oscillations, with a negative voltage applied. The data reported tend to indicate that oscillations are originating at the filament).

d. Extend the range of investigation along the tube characteristic above saturation.

e. Investigate further any possible connection between the low and high frequency oscillations. Observations using a photomultiplier should enable one to determine if moving striations are present and whether they are associated with the low frequency oscillations.

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